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A Four Cylinder Stirling Engine Computer Program With Dynamic Energy Equation

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May 1983

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

NF00357

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     E-1348 NAS 1.15:83053 DOE/NASA/52040-44   CNT#: DE-AI01-77CS-51040
     83/05/00  65 PAGES   UNCLASSIFIED DOCUMENT
UTTL: A 4-cylinder Stirling engine computer program with dynamic energy
     equations   TLSP: Final Report
AUTH: A/DANIELE, C. J.;  B/LORENZO, C. F.
CORP: National Aeronautics and Space Administration, Lewis Research Center,
     Cleveland, Ohio.    AVAIL.NTIS   SAP: HC A04/MF A01
MAJS: /*COMPUTATIONAL FLUID DYNAMICS/*COMPUTERIZED SIMULATION/*DYNAMIC MODELS/*
     STIRLING CYCLE/*THERMODYNAMICS
MINS: / CONTINUITY EQUATION/ FLOW CHARTS/ FLOW RESISTANCE/ HYDROGEN/ USER
     MANUALS (COMPUTER PROGRAMS)
ABA:  Author
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DOE/NASA/51040-44
NASA TM-83053

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Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-77CS51040

N83-26017*

A FOUR-CYLINDER STIRLING ENGINE COMPUTER PROGRAM WITH DYNAMIC ENERGY EQUATIONS

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SUMMARY

A computer program for simulating a four-cylinder Stirling engine is presented. The thermodynamic model includes both continuity and energy equations and simplified, first-order momentum terms (flow resistance). Drive dynamics and vehicle load effects are included. The computer program includes a model of a hydrogen supply system to accelerate the engine.

The simulation can generate, at the user's option, steady-state or transient data. Steady-state power and torque predictions compare well with experimental data over a wide range of engine speeds and pressures. Simulated acceleration data compare well with results from a simplified four-cylinder model that was previously developed by the authors. Complete flow charts are provided.

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INTRODUCTION

This report documents a computer program for simulating the steady-state and transient performance of a Stirling engine and serves as a users manual for the computer program. The evolution of the model is described below.

Stirling engine simulations have been developed for predicting steady-state engine performance. The simulations are based on the solution of the governing aerothermodynamic equations and are therefore quite complex. Pressure drops due to fluid flow resistance within the engine and to heat transfer coefficients between the heat exchangers and fluid and between fluid and the casing are calculated continuously during a cycle. Stirling engine performance is very sensitive to these factors.

Usual Stirling engine models include only two pistons and the working space between them. For analysis, the working space is usually segmented into control volumes corresponding to engine components - expansion space, heater, regenerator, cooler, and compression space. More than one control volume may be used to describe each component. Also, various heat transfer paths are included in the model. While many Stirling engines have more than one working space, the models used to predict performance generally do so for a single working space, and the resultant output power is multiplied by the number of working spaces. One such model has been developed by Tew, Jeffries, and Miao (ref. 1). It contains 13 control volumes in the working space. In that model, the energy equation is integrated within each control volume, while the pressure is assumed constant throughout the working space

over a cycle. Pressure drops throughout the engine are then back-calculated once the temperature distribution is known.

Although this approach is acceptable for performance calculations, it has shortcomings when the constant pressure assumption cannot be used, such as when the amount of hydrogen within a working space varies during a cycle. In a multicylinder engine, this can occur when transients are run from one operating point to another. Daniele and Lorenzo (ref. 2), as a first step in deriving a transient engine model, developed a model that can account for a change in the hydrogen-stored mass during a cycle. As in the Tew model, only one working space and two pistons are simulated. However, the number of control volumes in the working space is reduced to seven, one each for the expansion space, the heater, the cooler, and the compression space, and three for the regenerator. In that model, a thermal time constant associated with the regenerator mesh is included. Flow resistances and heat transfer coefficients are held constant over an engine cycle. Values of these parameters are specified as input data, using average values over a cycle, calculated from the output of Tew's model. Within each control volume, the continuity and energy equations are integrated and a simplified, first-order momentum term (flow resistance) is calculated. Upwind differencing (ref. 3) is used to calculate the interface volume temperatures for use in the energy equation. The resultant model has 17 state variables and uses a backward-difference integration scheme for problem solution. Results generated by that model compare well with experimental power and torque data over a wide range of speeds and pressures.

The aforementioned modeling approach (i.e., those in which only one working space is simulated) produces acceptable steady-state (power and torque) predictions when the working spaces in the engine are isolated. However, proposed controls schemes for four-cylinder Stirling engines require fluid transfer between working spaces. A more complete four-cylinder model is needed to analyze these control schemes.

One such four-cylinder model is also described in reference 2. In that model, each working space is further simplified to reduce computer run time. This simplification involves (1) reducing the number of control volumes in a working space from seven to three, (2) keeping the temperature within a control volume constant, and (3) assuming that the gas and regenerator mesh temperatures are equal. Steady-state results from this model are presented in references 2 and 4 and agree reasonably well with experimental data. The model was used to study various transient phenomena (ref. 4), and the associated computer program is documented in reference 5.

The simplified four-cylinder model is well suited for controls studies since it can produce transient results reasonably fast. Thus, many different cases can be run without using excessive computer time. However, the model lacks temperature variability, which may be important when simulating proposed control schemes, such as the injection of working fluid at one temperature into a control volume with resident working fluid at a different temperature.

To overcome this deficiency, the seven-volume, single-working-space model discussed earlier was extended to include all four pistons and working spaces; the resultant model is the subject of this report. A backward-difference integration scheme was used to account for the widely varying time constants associated with the flow and temperature dynamics. The integration scheme makes use of a multivariable Newton-Raphson iteration method (ref. 6) for convergence at a time point. To speed calculations, the Broyden update algorithm (ref. 7) was used to update the inverted Jacobian matrix during a transient.

This paper documents the seven-volume, four-working-space model and its computer implementation. A users manual and a test case are provided, along with complete flow charts. Results from the simulation are compared with results from the simplified four-cylinder model.

MODEL DESCRIPTION

The model consists of three parts: thermodynamic, drive geometry, and hydrogen supply. A schematic of the seven-volume, four-cylinder Stirling engine thermodynamic model is shown in figure 1. Each working space contains seven volumes - one each for the expansion space, the heater, the cooler, and the compression space, and three for the regenerator. A thermal time constant for the regenerator mesh is associated with each regenerator gas volume. Within each control volume, the continuity and energy equations are solved and a simplified first-order momentum term (flow resistance) is calculated. Upwind differencing is used to calculate interface volume temperatures (primed temperature variables in fig. 1) for use in the energy equation. All symbols shown in figure 1, as well as a complete symbols list, are given in appendix A. The equations used to model the engine are given in appendix B.

A schematic of the drive dynamics is shown in figure 2. Differential forces on the pistons are translated into torque through the vehicle drive geometry and summed to form total indicated torque. Torque due to engine friction is subtracted to form brake torque. This torque is available to drive auxiliaries and the vehicle load. The vehicle inertia and gear ratio are used in computing the effective load. The net torque is integrated once to give engine speed (PSIDT) and once again to give crank angle (PSI). The crank angle is used to generate piston position (using the crank geometry). The model can be run in this manner, or piston position can be forced as a function of time with torque and cycle performance calculated at constant speed.

A model of the working fluid supply system is shown in figure 3. This system is actually part of a mean pressure control system which modulates engine power by changing the amount of working fluid in the cycle. In order to accelerate the engine, working fluid is supplied to the engine. A slot in the piston rod is used to time the injection of working fluid into the various compression spaces in the engine. The timing is arranged to supply the fluid only when the pistons are near bottom (minimum) stroke. During this period, the pressure in the associated compression space is near a maximum, and the injected fluid functions to increase rather than decrease the engine torque. The check valves (fig. 3) remain open as long as the supply pressure (PSOURC) is greater than the corresponding compression space pressure. Also included in the supply model are rod leakage effects. These are indicated by WSSCN in figure 3 and allow study of the effects of mistimed flow injection into the system.

Simulation Flow Diagram

The overall simulation structure is shown in figure 4. Run conditions are set in MAINST. Subroutine ICSTIR is then called to calculate initial conditions. PISTIN is called from ICSTIR to calculate the initial piston position. ICSTIR then calls INTEGR, which is the integration subroutine. INTEGR handles the incrementing of time, data output, and run termination. INTEGR calls the Stirling engine simulation subroutine STIRSM to obtain the information it needs for the Jacobian matrix that is required by the backward-difference integration. STIRSM calls TORLOS to calculate engine friction, auxiliary losses, and vehicle load effects; PISTIN, to calculate piston positions from crank angle and crank geometry; and HYSUPY, to calculate flow into the engine, the phasing of the injected flow, and rod leakage effects. STIRSM then returns to INTEGR.

In figure 4 the body of INTEGR is shown within a dashed line. The subroutines enclosed are actually subroutines to INTEGR. While they are called by and return to INTEGR, they are shown as calling one another to illustrate the looping that takes place within the subroutine. Once a Jacobian matrix is calculated, INTEGR calls DMINV for a matrix inversion, or BRYDON for updates to a previously generated matrix. Subroutine BRYDON contains the Broyden update algorithm. This algorithm permits the simulation operating point to be changed without having to calculate a new Jacobian matrix. The algorithm does this by continually updating the known inverted Jacobian matrix. This can significantly reduce the computation time, since generating Jacobian matrices and inverting the matrices can be very time consuming. The use of the algorithm will be discussed in more detail later.

Convergence is then checked. If the simulation is not converged, more passes are made through INTEGR to generate better iteration guesses or, if necessary, a new Jacobian matrix. If converged, INTEGR calls TRAP to do a trapezoidal integration on the product of the pressure and volume in both the expansion and compression spaces. TRAP returns to INTEGR, which then calls OUTSTR if a printout is desired at the current time. OUTSTR returns to INTEGR; then GUESSE is called to predict the next set of state variables for the next time step. This is done until the desired maximum number of time steps have been run, at which time INTEGR terminates the run. Flow charts for all subroutines are given in appendix C.

Program Setup

The program setup is done in the main program MAINST. Switches are set to indicate the type of transient desired. Engine geometry and flow data are input data. Tables I to XIII indicate the required input as well as the options available. In table I, baseline engine geometry data are listed. The total regenerator volume (VR) excludes the volume of the mesh. Tables II to IV list the required heater, cooler, and regenerator data, respectively. The initial guesses for the temperature distribution within a working space are shown in table V. All four working spaces start out with this distribution as a first guess. All of the simulation constants are listed

in table VI. Flow resistances between the volumes are shown in table VII. Hydrogen constants are listed in table VIII. Data for the implicit integration method are listed in table IX. In most cases, the indicated integration settings should lead to convergence. However, experience has shown that increasing MPAS and/or TOLPCG can be helpful for difficult convergence problems.

Another method of overcoming convergence problems is to increase TOLSS. This is done internally in the program if the number of iterations using one matrix exceeds 20 passes, or if a new matrix needs to be generated. Once the program converges, TOLSS is set back to .0001 for the next time point. If MPAS is exceeded, the simulation will continue to run, but will produce a debug output at that time point indicating that MPAS has been exceeded.

The different switch options available can be selected by a set of switches defined in table X. Table XI lists all the run conditions that must be specified, while table XII defines the load characteristics. The cycle data are defined in table XIII. Note that if a supply transient is not desired, NCYSUP and NCYSTP from table XI must be set greater than NUMBCY.

Output Options

The user may select from a number of output options and a debug option. If ICALC = 1, a short printout is specified. The short printout header is shown in table XIV. Output variables include the heater temperature (TWH), cooler temperature (TWC), cycle mean pressure (CYCLPR), engine drive mode (NONENG), number of cycles to be run (NUMBCY), piston rod leakage area (ALEAK), supply pressure (PSOURC), hydrogen supply temperature (TSOURC), the time point to start the hydrogen supply (ISUPST), and the time point to end the hydrogen supply (ISPSTP).

Results are also printed at specified time steps. Power, torque, crank angle, mean pressure, and engine speed are printed. ITRAN indicates the number of time steps taken up to and including the printout; KWORK is a counter indicating the number of time steps in the calculation of the pressure-volume area (note that if KWORK = 201, 200 time steps were taken, since the first time step printed out is the initial condition).

If ICALC = 0, a long printout is specified; the long printout header is shown in table XV. At each specified time step a complete listing of all engine variables is generated. Note that the output is arranged in rows of four (except for the overall engine parameters). The first row corresponds to the first working space, the second corresponds to the second, etc. The output variables include all pressures, temperatures, and stored masses for each working space, as well as the power, torque, and supply flow. The last row of the long printout contains the same overall engine parameters as the short printout.

The user may select a debug option to aid in solving problems that may occur in the simulation. This option is specified in MAINST by NOBUG. If NOBUG = 1, the debug option will not be activated unless (a) there is a problem with convergence (the maximum number of iteration passes is exceeded without convergence), or (b) there is a problem in generating a partial derivative for the Jacobian matrix. The debug printout comes from STIRSM. The debug option is selected by the user by setting NOBUG = 0. A sample of the debug printout is shown in table XVI. This option is further described in appendix C.

OUTPUT - TEST CASE

Supply Transient

A supply transient is provided as an output test case. The assumed initial conditions for the transient are a mean pressure of 5 MPa and a speed of 2000 rpm. After 10 cycles, hydrogen is injected to accelerate the engine. The hydrogen supply pressure is 10 MPa and the supply temperature is 283 K. Piston rod leakage is assumed to be zero for this test case. The corresponding Fortran input for MAINST is shown in table XVII. The transient is defined by CYCLPR = 5, SPDRPM = 2000, NCYSUP = 10, NUMBCY = 100, PSOURC = 10, TSOURC = 10, and ALEAK = 0. The Broyden update algorithm is used (IBRYTH = 1), the step size is determined by the specified 200 points per cycle (NPTPCY = 200), and a short printout is desired every 200 points (ICALC = 1 and IPRTOP = 200).

The printout for this test case is given in table XVIII. Note that time is incremented so that the specified number of integration points per cycle is obtained. Therefore, the time step is a function of engine speed. Sixty-one engine cycles (12 201 time steps at 200 per cycle) were simulated before the specified limit on CPU time was exceeded. On the IBM 3033, the simulation ran for 60 min of CPU time, taking about 1 min of CPU time per engine cycle.

Figure 5 shows a comparison of acceleration results from this simulation (dashed lines) with results from the simplified model (solid lines). Data for power, torque, and mean pressure are plotted against time from the start of the hydrogen supply (both simulations were run for 10 cycles before supply input). At a 5 MPa mean pressure, the seven-volume model predicts more power (and thus more torque) than the simplified model (as seen by the steady-state maps of ref. 2). Thus, with the same load, losses, and gear ratios used on both simulations, the seven-volume model reaches steady-state at a higher speed than the simplified model.

At time equal zero in figure 5, the seven-volume model is running at 2400 rpm, while the simplified model is running at 2000 rpm. A hydrogen supply transient is then simulated in both cases, assuming a 10-MPa supply bottle. Pressure rises at about the same rate in both simulations. Power rises in both simulations at about the same rate, with the difference remaining fairly constant. Total torque also rises in both simulations. However, the difference between the total torques decreases slightly because of the difference in speed-torque maps as determined by each of the models. Both simulations give basically the same dynamic response; however, the three-volume model uses much less CPU time (about 1 sec of CPU time per cycle) because of its fewer state variables (14 versus 70).

Thus, both simulations are useful for controls analysis. The three-volume simulation (ref. 5) can be used for evaluating many control strategies or doing parametric studies, while the seven-volume simulation can be used to study detailed performance during specific controls transients.

Cycle Analysis

The simulation can be used to look at individual cycles. Results from a steady-state case (no supply) are shown in figure 6. Piston position, individual torques, total torque, compression space pressures, and compression space temperatures are shown. Speed is constant at 2000 rpm for this case. Results are similar to those presented for the simplified model in reference 4, except for the overall torque and compression space temperatures. Overall torque (fig. 6(c)), shows a low frequency oscillation at steady state which was not observed with the simplified (ref. 5) model. Further investigation, however, showed that the simulation had not quite reached steady state. Data are presented after eight engine cycles. The oscillations are approximately 1 N-m in 61 N-m, or about 1.6 percent. The reason for the torque oscillation is that the pressures within the working spaces are not at steady state, due to the slow response of the regenerator metal lumps (not included in the three-volume model).

Figure 7 shows the supply transient response of the engine with no piston rod leakage. The piston motion, individual torques, total torque, compression space pressures, compression space temperatures, supply flow, and rod leakage flow are plotted for three cycles. Again, results are similar to those presented for the simplified model in reference 4. Note, however, that compression space temperatures (fig. 7(e)) do drop because of the injection of cold working fluid and that compression space pressures (fig. 7(d)) rise because of the increase in stored mass. No torque droop is indicated in figure 7(c).

The same supply transient was run with a rod leakage area of 3.2 cm^2 (0.5 in^2); results are shows in figure 8. No torque droop is indicated in figure 8(c), even though there is a mistiming of the injected flow. Compression space temperatures, however, do fall more rapidly than in the nonleakage case.

CONCLUSIONS

A detailed seven-volume, four-working-space Stirling engine computer simulation has been developed. The simulation model includes drive dynamics and vehicle load effects. The simulation program includes subroutines which allow for simulation of control strategies, such as acceleration of the engine by adding hydrogen to the system.

All input data required to run the program are described. Flow charts of the overall simulation and the subroutines are also given. The simulation is modular to allow for easy modification of the model.

An input routine is provided in which the user specifies the transient to be run and supplies the necessary engine geometry data. The type of output is also selected by the user. Very detailed printouts at prescribed intervals can be selected; alternatively, less detailed printouts can be selected. The integration step size and the printout interval do not have to be the same.

Simulation test cases have been run, and results have been compared with results obtained from a simplified three-volume simulation. The simulations produce similar results, with the more detailed simulation (with

temperature dynamics) exhibiting more engine output power than the simplified simulation at the same engine speed and pressure. The detailed simulation shows variations in compression space temperature due to injected mass; the simplified simulation has no temperature variation.

The detailed simulation can be used to predict steady-state or transient performance of the engine. Engine accelerations can be run with or without piston rod leakage. The acceleration data presented herein can be used to verify the transient operation of the simulation program when actual engine data become available.

APPENDIX A

NOMENCLATURE

Engineering symbols

A	area, m^2
A_d	piston area, cm^2
A_r	rod area, cm^2
C_p	specific heat at constant pressure, J/(kg-K)
C_v	specific heat at constant volume, J/(kg-K)
F	force, N
G	gear ratio
h	heat transfer coefficient, $J/(sec\text{-}m^2\text{-}K)$
I	inertia, $N\text{-}m\text{-}sec^2$
J	mechanical equivalent of heat, 1.0 (N-m)/J
ℓ	piston stroke, m
P	pressure, N/m^2
Q	heat flow rate, J/sec
R	gas constant, (N-m)/(kg-K)
R_L	connecting rod length, m
S	fluid resistance, $(N\text{-}sec)/(kg\text{-}m^2)$
T	temperature, K
t	time, sec
τ	torque, N-m
V	volume, m^3
Vel	vehicle velocity, km/hr
w	mass, kg
$\dot{w}$	mass flow rate, kg/sec
$\dot{w}_{1,1}$; $\dot{w}_{1,2}$; $\dot{w}_{1,3}$; $\dot{w}_{1,4}$	flow rate from expansion space to heater, kg/sec
$\dot{w}_{2,1}$; $\dot{w}_{2,2}$; $\dot{w}_{2,3}$; $\dot{w}_{2,4}$	flow rate from heater to 1st regenerator, kg/sec

$\dot{W}_{3,1}$; $\dot{W}_{3,2}$; $\dot{W}_{3,3}$; $\dot{W}_{3,4}$	flow rate from 1st regenerator to 2nd regenerator, kg/sec
$\dot{W}_{4,1}$; $\dot{W}_{4,2}$; $\dot{W}_{4,3}$; $\dot{W}_{4,4}$	flow rate from 2nd regenerator to 3rd regenerator, kg/sec
$\dot{W}_{5,1}$; $\dot{W}_{5,2}$; $\dot{W}_{5,3}$; $\dot{W}_{5,4}$	flow rate from 3rd regenerator to cooler, kg/sec
$\dot{W}_{6,1}$; $\dot{W}_{6,2}$; $\dot{W}_{6,3}$; $\dot{W}_{6,4}$	flow rate from cooler to compression space, kg/sec
γ	ratio of specific heats
Δ	change in
Ψ	angular position

Subscripts:

a	auxiliaries
c	cooler
d	drag
e	engine
f	mechanical friction
h	heater wall
i	position in working space
in	into
j, k	working space
m	mesh
out	out of
p	piston
r	rod
rr	rolling resistance
s	stored
sup	supply
vol	gas volume
w	wheel
0	dead volume

Superscripts:

'	intervolume
·	derivative

Computer Variables

AD	piston area, cm^2
ADS1, ADS2, ADS3, ADS4	slot area in piston rods, cm^2
AJ	mechanical equivalent of heat, 1.0 (N-m)/J
ALEAK	piston rod leakage area, cm^2
ALPHA	crank angle lag, deg
AR	piston rod area, cm^2
AWC	cooler heat transfer area, cm^2
AWH	heater heat transfer area, cm^2
AWR	regenerator heat transfer area, cm^2
BIGNUM	scalar for matrix predictor (biggest number)
$\overline{CMAT}$	scratch matrix in BROYDEN algorithm
CP	specific heat at constant pressure, J/(kg-K)
CVM	specific heat of the mesh, J/(kg-K)
CYCLPM	maximum cycle pressure, MPa
CYCLPR	current cycle pressure, MPa
DEGR	conversion factor, rad/deg
DELT	time change, sec
$\overline{DELTAV}$	vector change in guess variables
$\overline{DELX}$	vector change in guess variables (BROYDEN algorithm)
$\overline{DELY}$	vector change in error variables (BROYDEN algorithm)
$\overline{E}$	error vector
$\overline{EMAT}$	jacobian matrix for 70th order system
$\overline{ERRBSE}$	past error vector
FDRAG	force due to drag, N
FORC1, FORC2, FORC3, FORC4	piston forces, N
FRAC	external control for matrix convergence
FRRF	force due to rolling resistance, N
G	gravitational constant, kg/(MPa-sec^2)
GAMMA	ratio of specific heats

GR	gear ratio
GRAT	overall gear ratio
GTRAN	transmission gear ratio
HC	cooler heat transfer coefficient, $J/(sec-cm^2-K)$
HH	heater heat transfer coefficient, $J/(sec-cm^2-K)$
HR	regenerator heat transfer coefficient, $J/(sec-cm^2-K)$
IBRYTH	switch for BROYDEN algorithm
ICALC	switch for output printout
ICON	counter for converged errors
IHPCNV	switch for matrix generation at every point
INDICA	switch for sign change on guess variable
IPRTOP	switch for the number of printouts per cycle
IROT	switch for indicating a complete crank rotation
ISPSTP	time point for stopping supply
ISS	switch for initial conditions
ISUPST	time point for start of supply transient
ITRAN	counter for time steps
ITRMAX	maximum number of stime steps
KBROY	counter for calls to the BROYDEN algorithm
KWORK	number of points in pressure-volume integration
KWRIT	counter for printout
MATRIX	switch for generating a new Jacobian matrix
MATTOT	counter for the number of matrices generated during a transient
MPAS	maximum allowable iteration passes
N	system order
NCYSTP	cycle at which to end supply
NCYSUP	cycle at which to start supply
NITER	counter for the number of iterations at a time point
NMAT	counter for the number of Jacobian matrices generated at a time point
NOBUG	switch for a debug printout
NONENG	type of piston motion 0 forced 1 calculated

NPTPCC	number of integrations per cycle plus one
NPTPCY	number of integrations per cycle
NSTP	switch for storing past converged scale factors for iteration guesses
NTMAX	maximum number of iteration variables
NUMBCY	number of engine cycles to run
PAUX	power loss due to auxiliaries, MPa
PAVEMP	cycle pressure, MPa
PC1, PC2, PC3, PC4	gas pressure in compression spaces, MPa
PCNCHG	iteration convergence rate
PCOLD1, PCOLD2, PCOLD3, PCOLD4	gas pressure in cooler spaces, MPa
PDRAG	power loss due to vehicle air drag, kW
PENG	total power loss due to friction and auxiliaries, kW
PE1, PE2, PE3, PE4	gas pressure in expansion spaces, MPa
PFRICT	power loss due to engine friction, kW
PH1, PH2, PH3, PH4	gas pressure in the heater spaces, MPa
PIE	constant (3.14167)
PLOAD	total power required by the load, kW
PNET	net power, kW
POSDEG	crank angle, deg
POSDEO	initial condition crank angle
POWERT	total engine power output, kW
PRRF	power loss due to rolling resistance, kW
PR11, PR12, PR13, PR14	gas pressure in first regenerator spaces, MPa
PR21, PR22, PR23, PR24	gas pressure in second regenerator spaces, MPa

PR31, PR32, PR33, PR34	gas pressure in third regenerator spaces, MPa
PSI	crank angle, rad
PSIDDT	crank angle acceleration, rad/sec^2
PSIDT	crank angle velocity, rad/sec
PSOURC	hydrogen supply pressure, MPa
PWR1, PWR2, PWR3, PWR4	power out of cylinders, kW
QC1, QC2, QC3, QC4	cooler heat flow rate, J/sec
QH1, QH2, QH3, QH4	heater heat flow rate, J/sec
R	gas constant, (MPa-cm^3)/(K-kg)
RANK	change centigrade to kelvin
RAT	scaler change on step size for iteration
RATIO	largest step size change
REF	desired value of the summation of errors
RODL	crank rod length, cm
RST	flow resistance, (MPa-sec)/kg
RWHEEL	radius of car wheel, cm
SES	summation of squares of present errors
SESP	summation of squares of past errors
SPDMAX	maximum engine speed, rpm
SPDRPM	current engine speed, rpm
STROKE	piston stroke length, cm
TAUX	torque loss due to engine auxiliaries, N-m
TCO	initial compression space temperature, K
TC1, TC2, TC3, TC4	gas temperature in compression spaces, K
TCOLDO	initial cooler space temperature, K
TCOLD1, TCOLD2, TCOLD3, TCOLD4	gas temperatures in cooler spaces, K

TDRAG	torque loss due to vehicle air drag, N-m
TEMP	Broyden update scalar
TEMP1	Broyden update scalar
$\overline{\text{TEMP2}}$	Broyden update vector
$\overline{\text{TEMP3}}$	Broyden update vector
TENG	total torque loss due to engine auxiliaries and friction, N-m
TEO	initial expansion space temperature, K
TE1, TE2, TE3, TE4	gas temperatures in expansion spaces, K
TFRICT	torque loss due to engine friction, N-m
THO	initial heater temperature, K
TH1, TH2, TH3, TH4	gas temperature in heater spaces, K
TIME	time, sec
TLOAD	total torque loss required by the load, N-m
TNET	net torque, N-m
TOLPCG	convergence rate at which a decision is made to generate a new Jacobian matrix
TOLSS	error tolerance
TOL1	lower limit for good partial derivative
TOL2	upper limit for good partial derivative
TORQT	total engine torque, N-m
TORQ1, TORQ2, TORQ3, TORQ4	individual torques, N-m
TRRF	torque loss due to rolling friction, N-m
TR10	initial regenerator gas temperature, K
TR11, TR12, TR13, TR14	first regenerator space temperature, K
TR20	initial regenerator gas temperature, K
TR21, TR22, TR23, TR24	second regenerator space temperature, K
TR30	initial regenerator gas temperature, K

TR31, TR32, TR33, TR34	third regenerator space temperature, K
TRQ1, TRQ2, TRQ3, TRQ4	individual piston torques, N-m
TSOURC	working fluid source temperature, K
TWC	cooler wall temperature, K
TWH	heater wall temperature, K
TWR11, TWR12, TWR13, TWR14	mesh temperature in first regenerator segments, K
TWR21, TWR22, TWR23, TWR24	mesh temperature in second regenerator segments, K
TWR31, TWR32, TWR33, TWR34	mesh temperature in third regenerator segments, K
$T'_{1,1}$; $T'_{1,2}$; $T'_{1,3}$; $T'_{1,4}$	intervolume temperature between expansion space and heater space, K
$T'_{2,1}$; $T'_{2,2}$; $T'_{2,3}$; $T'_{2,4}$	intervolume temperature between heater space and first regenerator space, K
$T'_{3,1}$; $T'_{3,2}$; $T'_{3,3}$; $T'_{3,4}$	intervolume temperature between first regenerator space and second regenerator space, K
$T'_{4,1}$; $T'_{4,2}$; $T'_{4,3}$; $T'_{4,4}$	intervolume temperature between second regenerator space and third regenerator space, K
$T'_{5,1}$; $T'_{5,2}$; $T'_{5,3}$; $T'_{5,4}$	intervolume temperature between third regenerator space and cooler space, K

$T'_{6,1}$; $T'_{6,2}$; $T'_{6,3}$; $T'_{6,4}$	intervolume temperature between cooler space and compression space, K
VC1, VC2, VC3, VC4	compression space volumes, cm^3
VCOLD	cooler volume, cm^3
$\overline{VCONV}$	vector of converged state variables from previous time step
VDELTA	initial perterbation of state variables
$\overline{VDOT}$	vector of state variable derivatives at current time step
$\overline{VDOTT}$	vector of average value of state variable derivatives
VE1, VE2, VE3, VE4	expansion space volumes, cm^3
$\overline{VGUESS}$	initial guess vector at each time step
VH	heater volume, cm^3
VKPH	car velocity, km/hr
$\overline{VMAT}$	vector of changes in guess variables during iteration
VOC	compression space dead volume, cm^3
VOE	expansion space dead volume, cm^3
VR	regenerator volume minus mesh, cm^3
$\overline{VS}$	guess vector during iteration
$\overline{VSAVE}$	vector of saved conveyed guess variables
$\overline{VWS}$	state vector
WSC1, WSC2, WSC3, WSC4	compression space stored masses, kg
WSCLD1, WSCLD2, WSCLD3, WSCLD4	cooler stored masses, kg
WSE1, WSE2, WSE3, WSE4	expansion space stored masses, kg
WSH1, WSH2, WSH3, WSH4	heater space stored masses, kg

WSM	mass of the mesh, kg
WSO1, WSO2, WSO3, WSO4	intermediate supply flows, kg
WSR11, WSR12, WSR13, WSR14	first regenerator stored masses, kg
WSR21, WSR22, WSR23, WSR24	second regenerator stored masses, kg
WSR31, WSR32, WSR33, WSR34	third regenerator stored masses, kg
WSS1, WSS2, WSS3, WSS4	supply flows, kg/sec
WSSCN1, WSSCN2, WSSCN3, WSSCN4	rod leakage flows, kg/sec
WSTOT1, WSTOT2, WSTOT3, WSTOT4	total supply flows, kg
WT1, WT2, WT3, WT4	stored mass in each working space, kg
WTCAR	mass of the car, kg
WTENG	mass of the engine, kg
WTOT	total stored mass, kg
WTWHEL	mass of the wheels, kg
XD1, XD2, XD3, XD4	piston positions, cm
XD(3)	piston 3 position, cm
XD30	piston 3 starting position, cm
XXX	summation of squares of the changes in the errors to the max error
$\overline{YYY}$	scalar vector for changes in guesses
$\overline{ZMAT}$	Jacobian matrix for 68th order system

APPENDIX B

MODEL EQUATIONS

The equations used to model the fluid dynamics and thermodynamics are ordinary differential equation approximations of the complex partial derivative flow equations. Mass flow is assumed to occur due to pressure differential between the gas nodes. In figure 1 the pistons are numbered in the order in which they reach top stroke, as is indicated by the arrows in the piston heads. A double subscript notation has been adopted in which the first subscript denotes a volume position within a working space, and the second subscript denotes the working space.

Representative equations are

$$\dot{w}_{i,j} = \frac{(P_{i,j} - P_{i+1,j})}{S_{i,j \to i+1,j}} \qquad \begin{matrix} j = 1,2...4 \\ i = 1,2...6 \end{matrix}$$

where the arrow indicates flow resistance measured between the volumes.

$$\dot{w}_{s_{i+1,j}} = \dot{w}_{i,j} - \dot{w}_{i+1,j} \qquad \begin{matrix} j = 1,2...4 \\ i = 0,1...6 \end{matrix}$$

$$\dot{w}_{0,j} = \dot{w}_{7,j} = 0.0$$

and

$$P_{i,j} = \frac{w_{s_{i,j}} R T_{i,j}}{V_{i,j}} \qquad \begin{matrix} j = 1,2...4 \\ i = 1,2...7 \end{matrix}$$

Volumes are assumed to vary with piston position. For volume 1 in working space 1

$$V_{1,1} = V_{1,1_0} + \left(\frac{\ell}{2} - x_1\right) A_p$$

Piston position is a function of crank angle:

$$x_i = \frac{\ell}{2}\cos\psi_i + \sqrt{R_L^2 - \frac{\ell^2}{2}\sin\psi^2_i} - \sqrt{R_L^2 - \frac{\ell^2}{2}} \qquad i = 1,2...$$

The energy equation used to calculate the change in temperature in a volume is complicated by the oscillatory nature of the Stirling cycle. The form of the equation is

$$w_{s_{i,j}} T'_{i,j} = \dot{w}_{i-1,j}(\gamma T'_{i-1,j} - T_{i,j}) - \dot{w}_{i,j}(\gamma T'_{i,j} - T_{i,j}) + \frac{Q_{i,j}}{c_v} + \frac{Work_{i,j}}{J_c}$$

where

$$j = 1,2...4$$
$$i = 1,2...7$$
$$\dot{w}_0 = \dot{w}_7 = 0$$

and where the heat flows into and out of the gas are modeled as

$$\dot{Q} = hA(\Delta T)$$

Primed temperature variables denote interface volume temperatures and are determined by upwind differencing (ref. 1). The method assumes that the gas temperature has the same temperature profile as the regenerator matrix temperature. Representative equations for positive and negative flows are

$$\left.\begin{aligned} \dot{w}_{i,j} \geq 0,\ T'_{i,j} &= T_{i,j} - \frac{(T_{m_{3,j}} - T_{m_{5,j}})}{4.0} + \frac{\dot{w}_i \Delta t (T_{m_{3,j}} - T_{m_{5,j}})}{4.0\, w_{s_{i,j}}} \\ \dot{w}_{i,j} < 0,\ T'_{i,j} &= T_{i+1,j} - \frac{(T_{m_{3,j}} - T_{m_{5,j}})}{4.0} + \frac{\dot{w}_i \Delta t (T_{m_{3,j}} - T_{m_{5,j}})}{4.0\, w_{s_{i+1,j}}} \end{aligned}\right\} \begin{matrix} j = 1,2...4 \\ 2 \leq i \leq 5 \end{matrix}$$

$$\left.\begin{aligned} \dot{w}_{i,j} \geq 0,\ T'_{i,j} &= T_{i,j} \\ \dot{w}_{i,j} < 0,\ T'_{i,j} &= T_{i+1,j} \end{aligned}\right\} \qquad i = 1,6$$

The regenerators are modeled as thermal lags:

$$T_{m_{i,j}} = \frac{h_i A_i}{c_{p_m} w_{s_m}} (T_{i,j} - T_{m_{i,j}}) \qquad \begin{matrix} j = 1,2...4 \\ i = 3,4,5 \end{matrix}$$

Torque is calculated as a function of differential forces on the pistons, which are summed through the drive geometry. A representative equation is

$$T_1 = \frac{\ell}{2} \left[P_{1,1}A_p - P_{7,2}(A_p - A_n)\sin \psi_1\right] \left(\frac{1 + \frac{\ell}{2} \cos_1 \psi_1}{\sqrt{R_L^2 - \frac{\ell}{2}^2 \sin^2 \psi_1}} \right)$$

Also included in the model are simplified vehicle load effects and engine power losses due to mechanical friction and auxiliaries. Figure 2 shows a schematic of how these losses are calculated. Torques from the pistons are summed to form indicated torque. Torque due to mechanical friction (TFRICT) is subtracted to form brake torque. The resultant torque is available for engine auxiliaries (TAUX) and also for vehicle load effects, such as rolling resistance (TRRF) and drag (TDRAG).

APPENDIX C

FLOW CHARTS

This appendix contains flow charts for the main program and all the subroutines of the simulation. Most flow charts are straightforward, with the possible exception of that for subroutine INTEGR. INTEGR performs both the incrementing of time and the integration of the state equations. The integration scheme is implicit. It is a backward-difference integration which uses a multivariable Newton-Raphson iteration for convergence at a time point. This type of integration is stable for both large and small step sizes. This stability is important when there is a large spread in eigenvalues for the system, which is the case when both pressure-flow and temperature dynamics are simulated. The implicit integration scheme can handle the widespread dynamics while insuring stability. To help one understand how subroutine INTEGR works, the following description is provided. To help one follow the INTEGR flow chart, statement numbers corresponding to the Fortran listing are given in the flow chart.

Integration Scheme

The integration scheme is a backward difference method which uses a multivariable Newton-Raphson iteration scheme for convergence. Guess variables are updated by using the old guess vector $\overline{VS}_{old}$, the current error vector $\overline{E}$, and an inverted Jacobian matrix $\overline{EMAT}$:

$$\overline{VS}_{new} = -\overline{EMAT}^{-1} \times \overline{E} + \overline{VS}_{old} \qquad (C1)$$

$\overline{EMAT}$ is a Jacobian matrix of partial derivatives (i.e., changes in error variables with respect to changes in state variables):

$$EMAT(I,J) = [E(J) - ERRBSE(J)]/DELTAV(I) \qquad (C2)$$

Updating takes place when the errors are converged within tolerance. With this technique, both steady-state and transient solutions can be obtained by redefining the error variables. In steady state all states are at rest; thus

$$\overline{VDOT} = 0.0 = \overline{E} \qquad (C3)$$

For a transient case

$$\overline{VDOT} \times DELT - (\overline{VS}_{new} - \overline{VS}_{old}) = \overline{E} \qquad (C4)$$

Equations (C3) and (C4) are converged when all the elements of $\overline{E}$ are with a specified tolerance. It should be noted that all the equations are scaled by the converged state to help convergence.

In order to use this method, a Jacobian matrix must be calculated (usually by finite differences) and then inverted. This can be very time consuming. Therefore, the logic in INTEGR allows for calculation of a new matrix only under adverse conditions. Examples might be (1) too low a convergence rate of the simulation (PCNCHG < TOLPCG), or (2) the number of allowable passes (MPAS) being exceeded. Also to speed convergence, the error tolerance (for eq. (C4)) is increased if more than one matrix must be calculated at the same time or if more than 20 passes are required using the same matrix. Once convergence is obtained, the tolerance is reset to its nominal value.

Perturbation Calculation

Several features in INTEGR help the implicit integration scheme converge. Of primary importance is the generation of a "good" Jacobian matrix. All the partial derivatives must be representative of the linear behavior of the system at a given operating point. Since finite differences are used, the sizes of the perturbations of the states are important: If the perturbations are too large, errors will be introduced by the system nonlinearities; if they are too small, the partial derivatives will be in error due to numerical problems (without double precision arithmetic).

Thus, a tuning mechanism has been introduced into INTEGR to optimize the sizes of the perturbation. First the sum of squares of all the changes in the errors is calculated for each perturbation. Once this is done, the "goodness" of the partial is checked by calculating

$$XXX = \frac{1}{N} \sqrt{\sum_{i=1}^{N} [E(I) - ERRBSE(I)]^2} \qquad (C5)$$

for each state variable and then checking if

$$TOL1 \leq XXX \leq TOL2 \qquad (C6)$$

If all XXX's fall within the tolerance band, the matrix is considered good. For this simulation, TOL1 = 0.001 and TOL2 = 0.01. Since all the errors are scaled, this tolerance band lies between 0.1 and 1 percent. For a more linear system, the band could be larger; for a more nonlinear system, smaller.

Scaling of Perturbations

In general, for the initial perturbations at a point, the XXX's will not fall in the tolerance band described above. Thus, INTEGR scales the perturbations to try to force the XXX's within the band. This is done by calculating

$$YYY = REF/XXX \tag{C7}$$

for each state variable. REF is defined as being the center of the tolerance band:

$$REF = \frac{(TOL1 + TOL2)}{2.0} \tag{C8}$$

Once a set of YYY's has been calculated such that the XXX's fall within the band, the set of YYY's is stored. After this has been done for all N states, the scaling vector $\overline{YYY}$ is generated. When a new matrix is needed, the scaling vector $\overline{YYY}$ is applied to the current states to determine first guesses for the perturbations needed to obtain new partial derivatives. If for any state variable the new XXX falls outside the tolerance band, YYY is updated and the new result stored. This method generally reduces the number of passes required for subsequent matrix generation.

Error Messages

In generating a partial derivative, a situation may arise where XXX never gets within tolerance. When this happens, the program prints an error message: "CHECK INPUT - BAD PARTIAL DERIVATIVE", prints a debug output to help the user diagnose the problem, and then stops the simulation. This is the only time when the simulation is stopped, except for the normal exit (i.e., ITRAN incremented to its maximum value, ITRMAX). In general, nonconvergence will occur when inconsistent coding is added to the simulation. One example would be if a piston ring leakage flow was calculated and subtracted from one working space but not added to the adjacent working space.

Another error message occurs when the simulation does not converge. This situation occurs when MPAS (set at 50) is exceeded. A message is printed; for example, "ITERATION FAILURE 69 51 32 15". The numbers printed out are the number of converged errors (may be any number from 0 to $N-1$; 69 is shown here), the number of iteration passes (MPAS + 1), the number of times the BROYDEN update algorithm has been called for the current matrix (32 here), and the point at which the convergence failed (ITRAN). In this situation, a debug output is printed from STIRSM which indicates

I	counter for the system order
VS	current guess variables
VCONV	past converged guess variables
VWS	state variables
VDOT	current state derivative
VDOTT	converged state derivative between current time point and past converged value
E	current errors

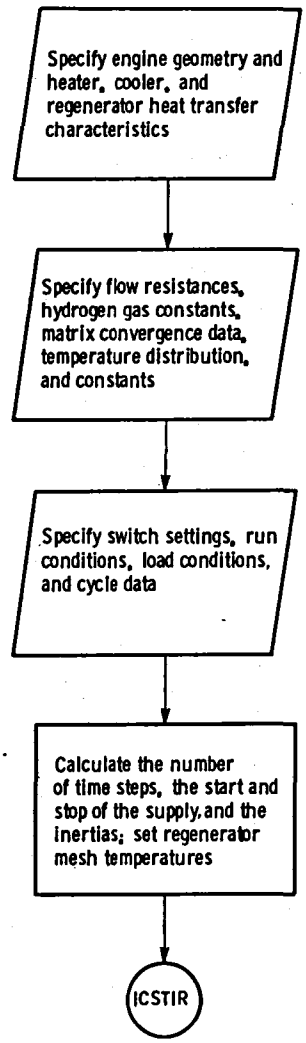
After the printout, the simulation continues. Note that with this method a convergence failure may occur, but the errors will be very close to the tolerance band. After the failure, the simulation may recover. For this reason the simulation is allowed to continue and the user may make a judgment as to the validity of the data after a convergence failure.

The occurrence of many convergence failures in a transient, however, usu- ally indicates a need for the user to increase tolerance or check his input and coding.

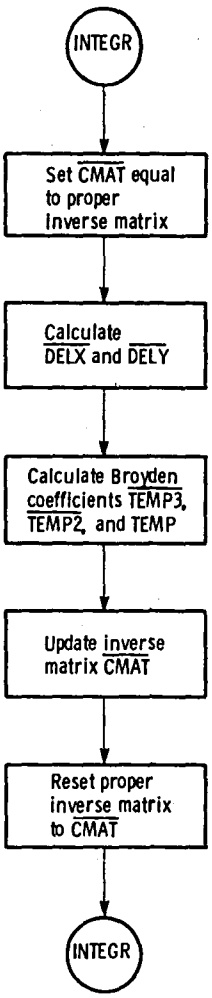
Broyden Update Algorithm

As stated earlier, it is time consuming to calculate a Jacobian matrix, and even more time consuming to invert a matrix for a large system. Usually double precision is required (as in DMINV). Lack of speed of the matrix inversion algorithm can be prohibitive, especially in a controls model where long transients are needed to evaluate controls schemes. One possible means of avoiding this problem is to generate the inverse, and then to continually update it with information gained as the inverse is used. One way to do this is by using the Broyden update algorithm, found in subroutine BRYDON. The use of the algorithm is controlled by IBRYTH, which is set in MAINST.

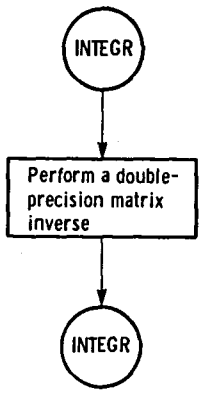
Main program MAINST



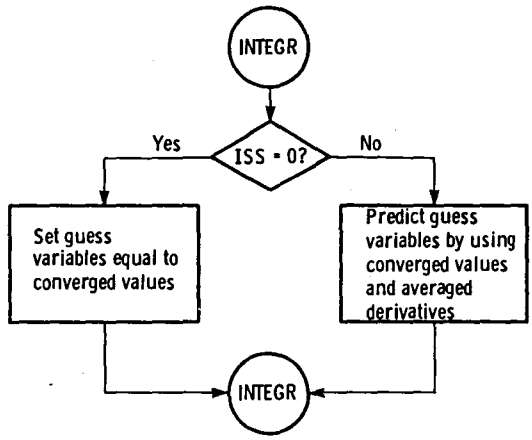
Subroutine BRYDON



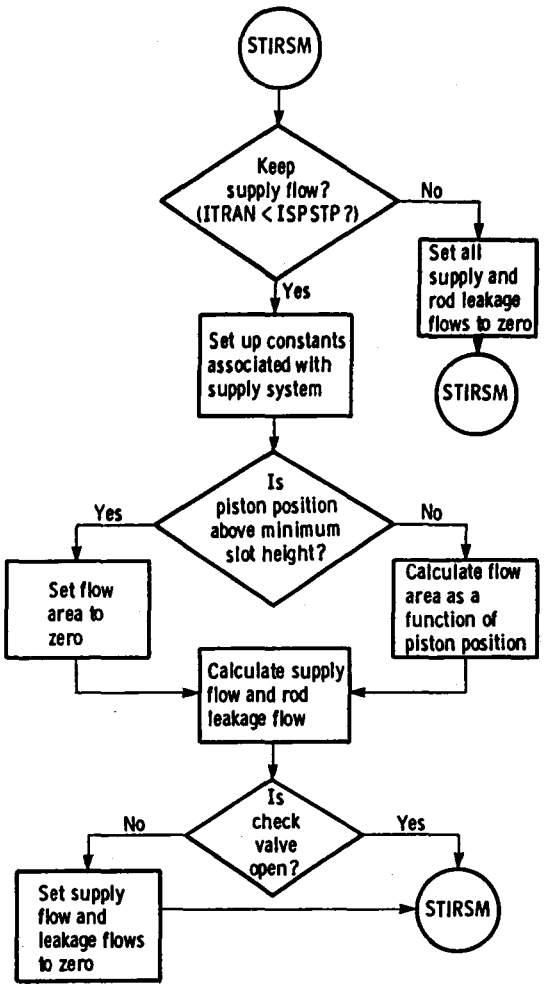
Subroutine DMINV



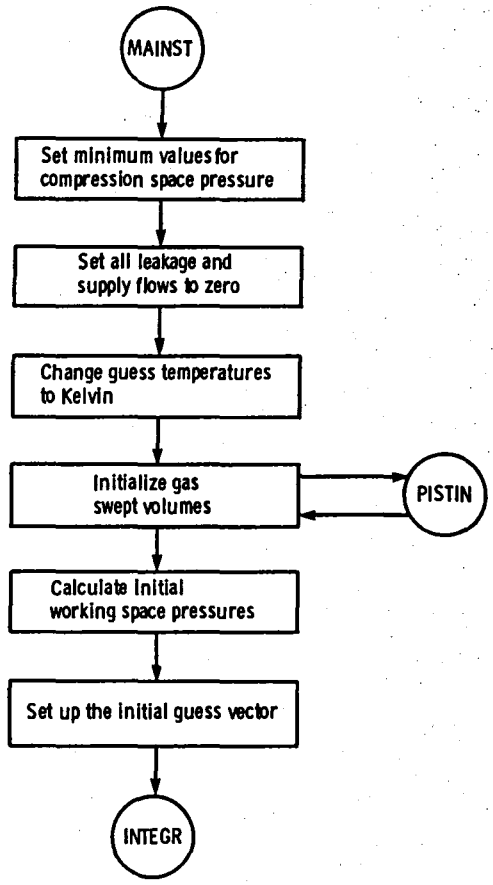
Subroutine GUESSE

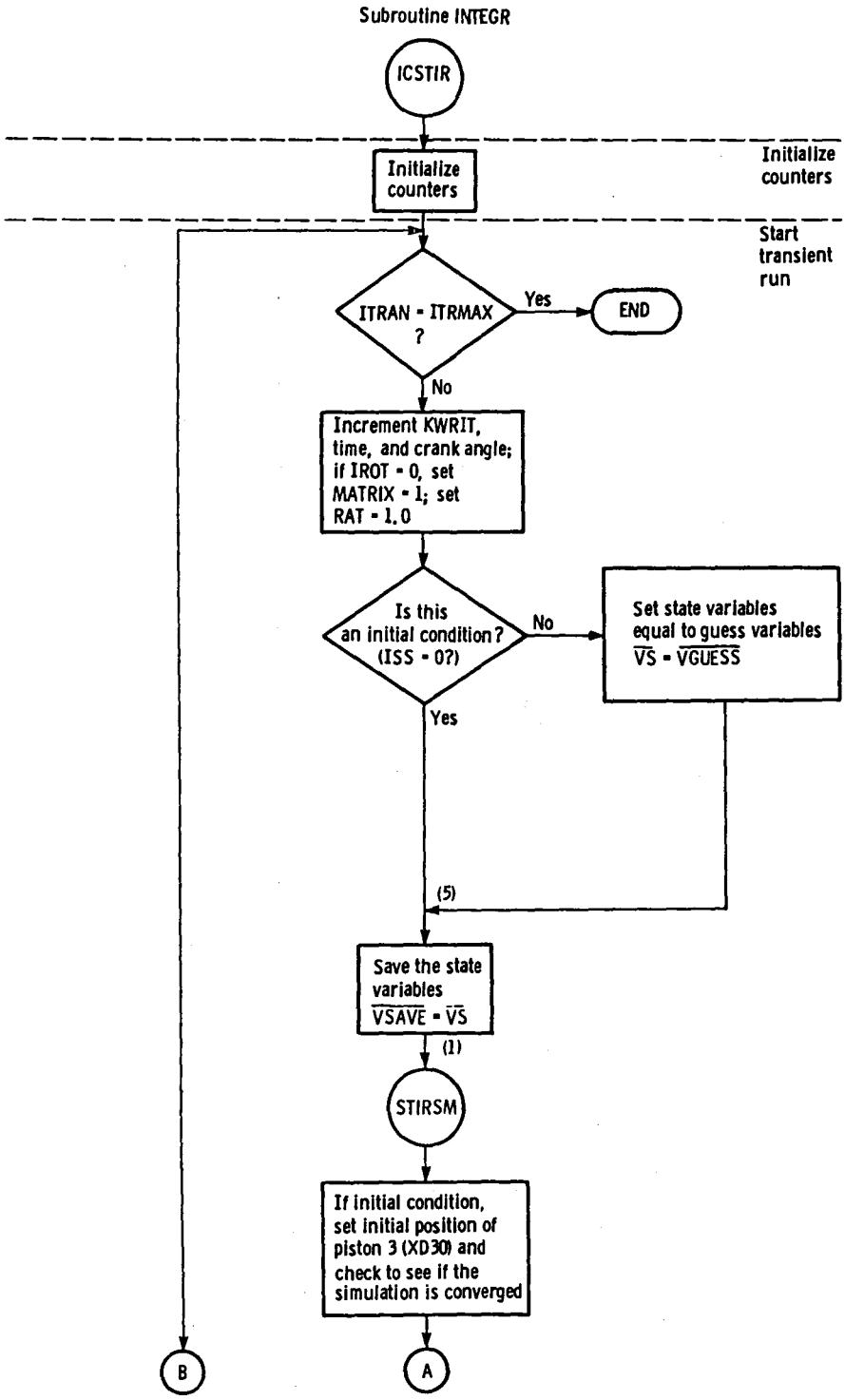


Subroutine HYSUPY

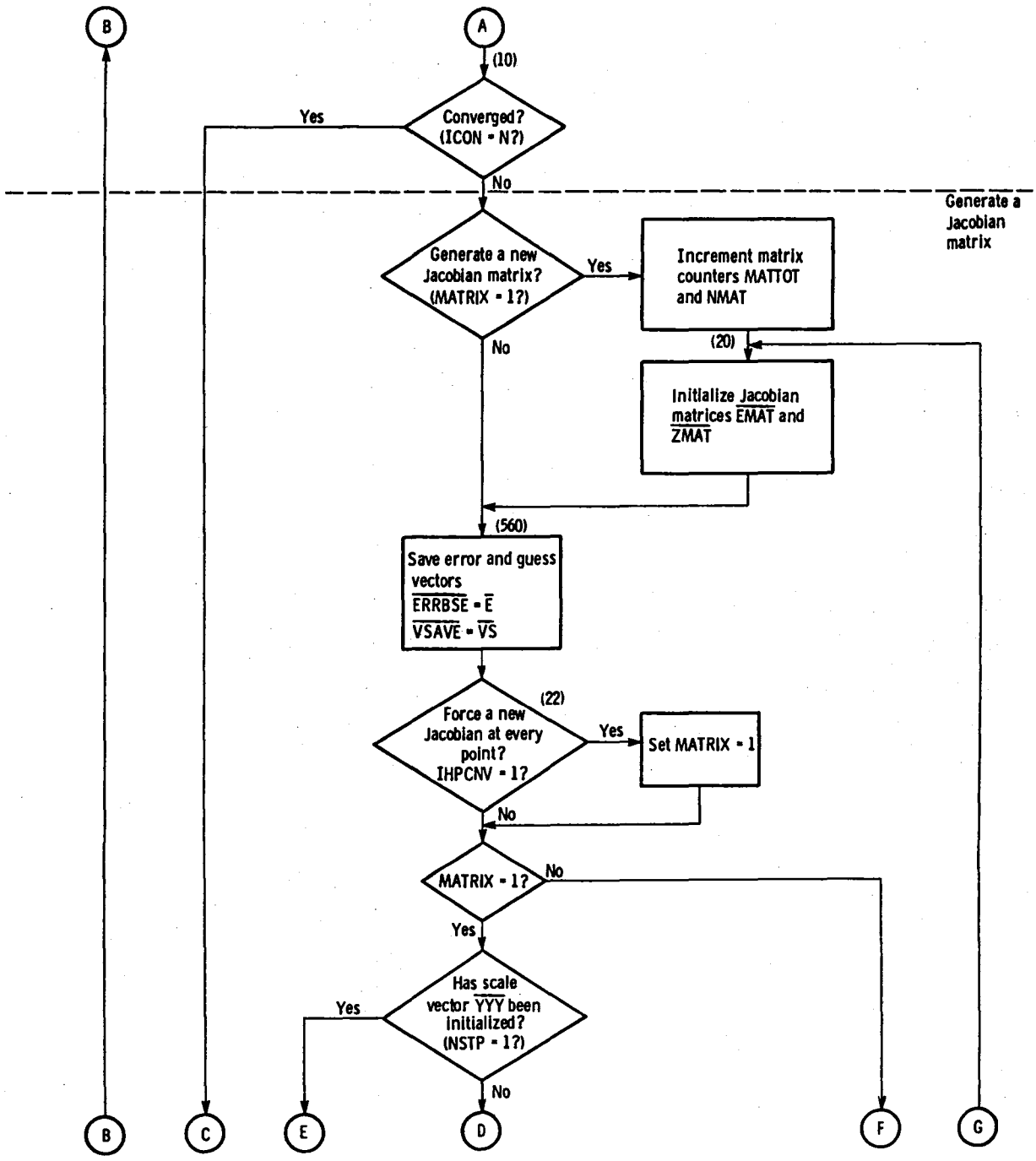


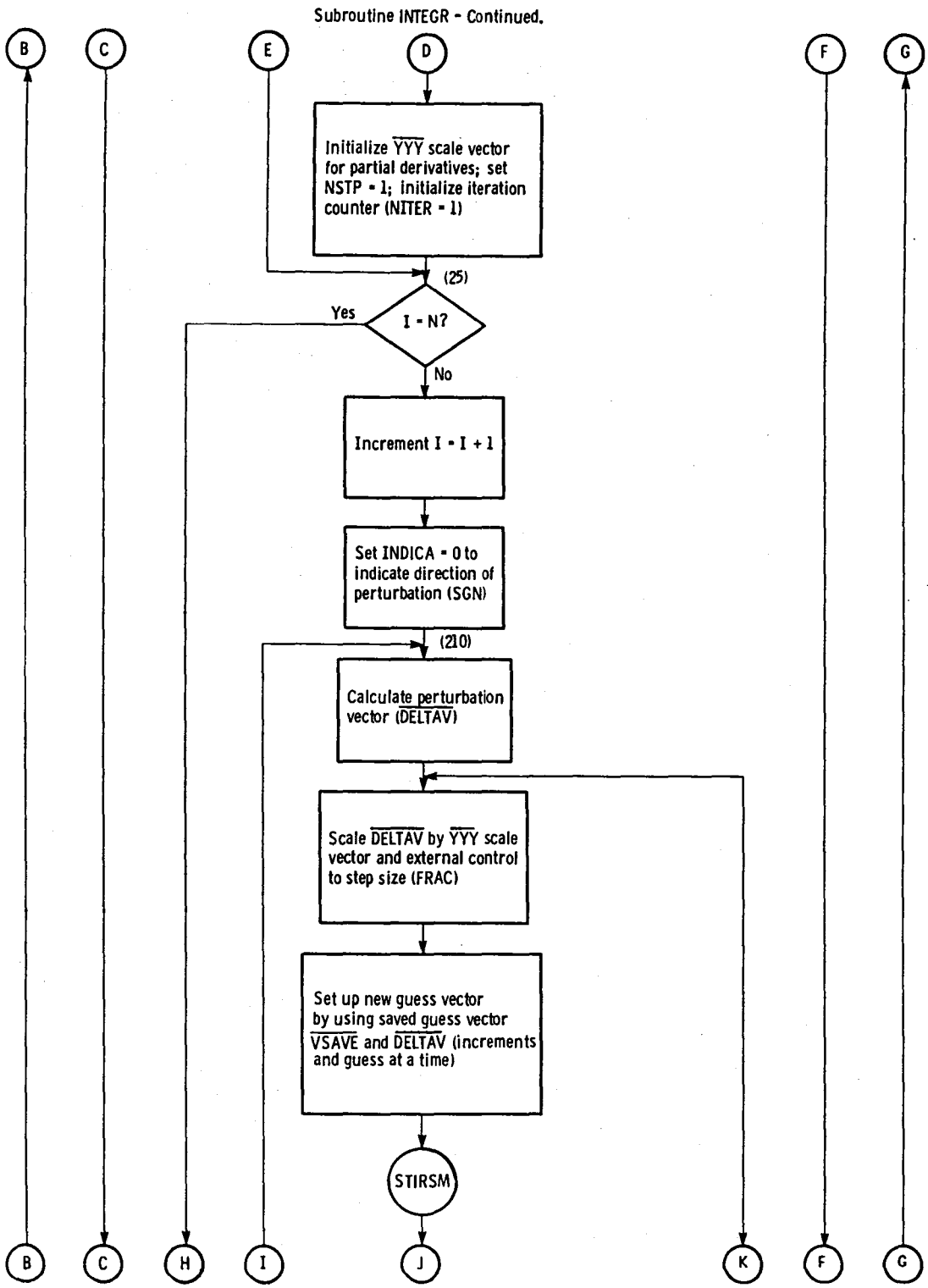
Subroutine ICSTIR



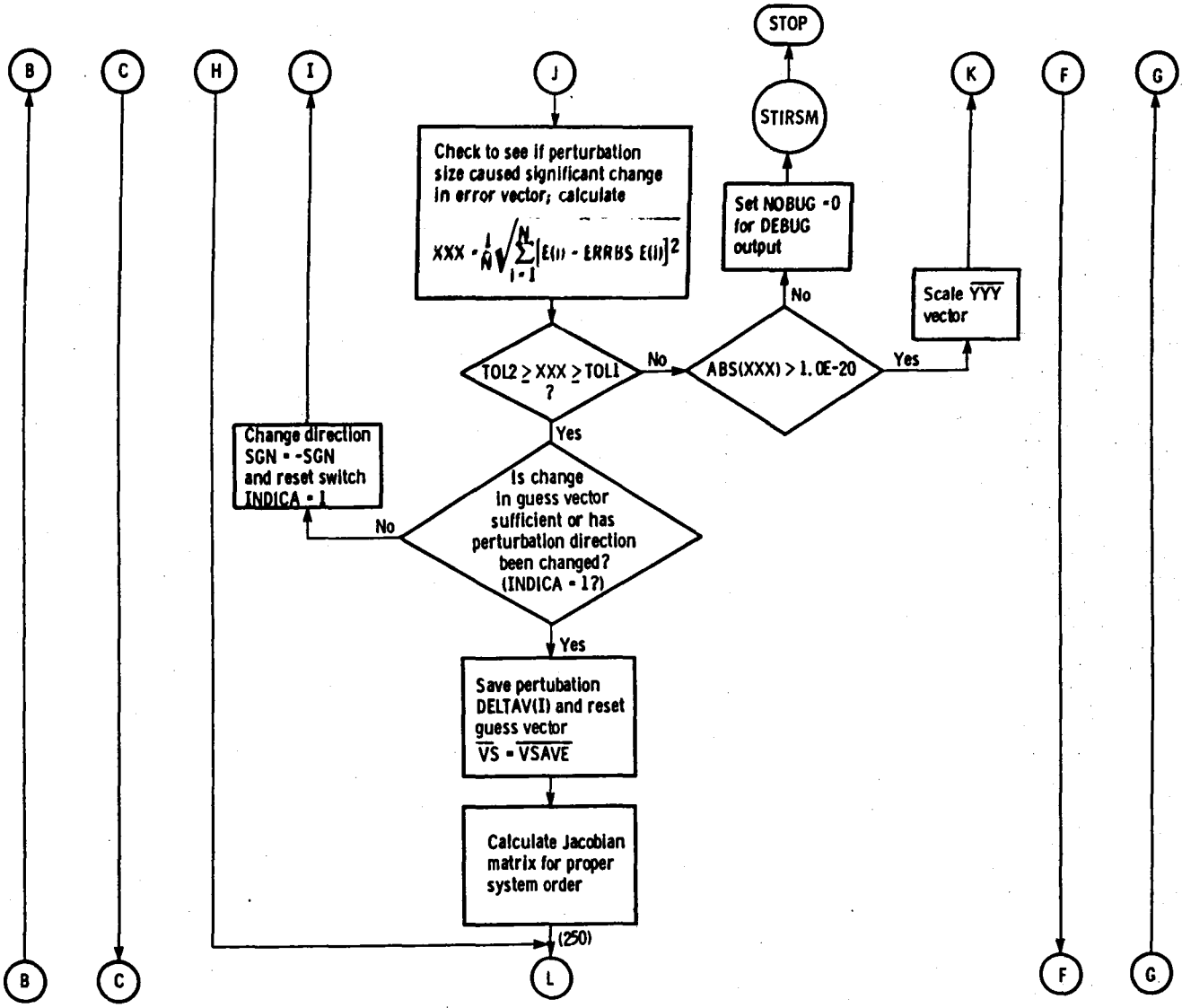

Subroutine INTEGR
ICSTIR
Initialize counters
Initialize counters
Start transient run
ITRAN = ITRMAX ?
Yes
END
No
Increment KWRIT, time, and crank angle; if IROT = 0, set MATRIX = 1; set RAT = 1.0
Is this an initial condition? (ISS = 0?)
No
Set state variables equal to guess variables VS = VGUESS
Yes
(5)
Save the state variables VSAVE = VS
(1)
STIRSM
If initial condition, set initial position of piston 3 (XD30) and check to see if the simulation is converged
B
A

Subroutine INTEGR - Continued.

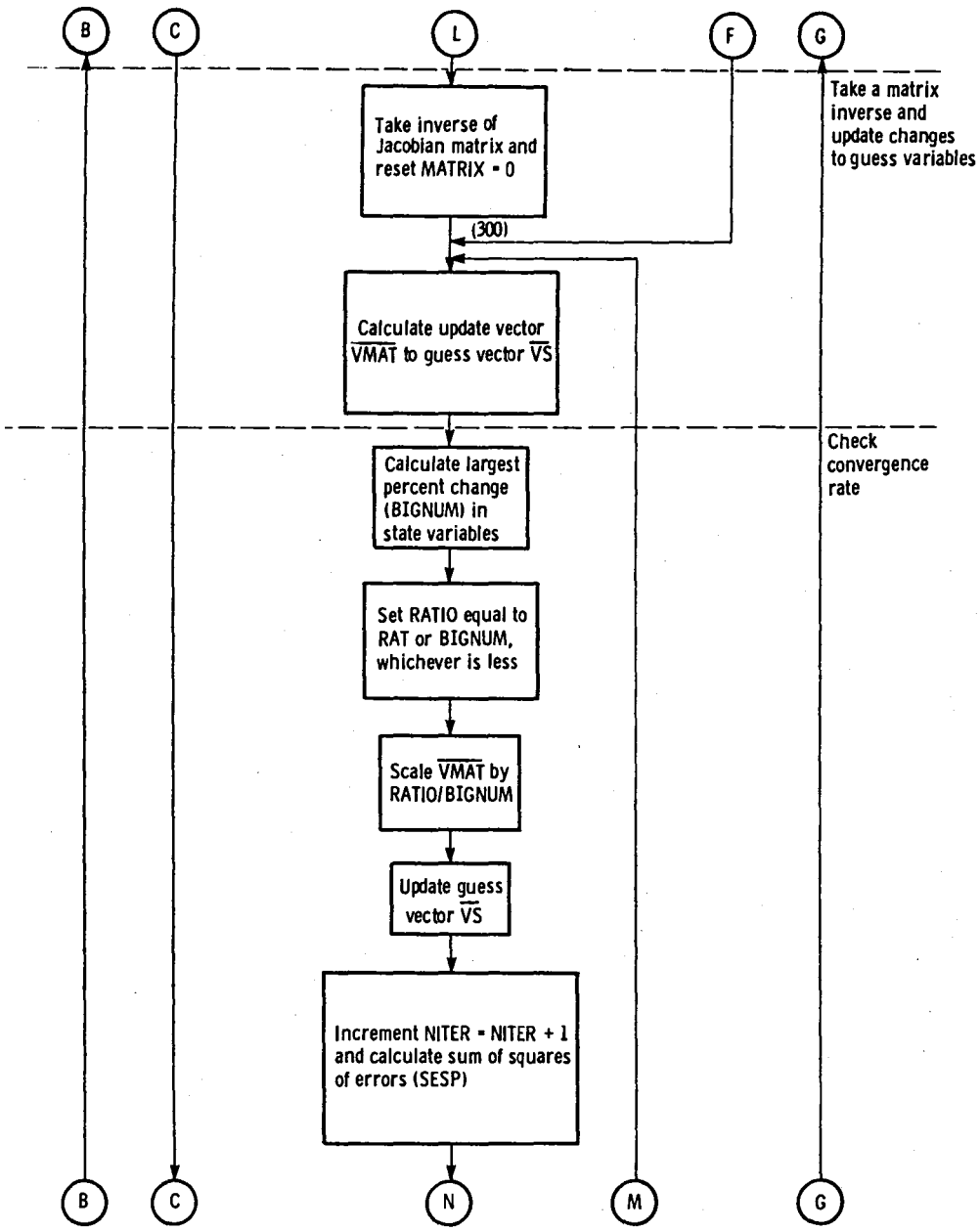



Subroutine INTEGR - Continued.
B
C
E
D
F
G
Initialize YYY scale vector for partial derivatives; set NSTP = 1; initialize iteration counter (NITER = 1)
(25)
Yes
I = N?
No
Increment I = I + 1
Set INDICA = 0 to indicate direction of perturbation (SGN)
(210)
Calculate perturbation vector (DELTAV)
Scale DELTAV by YYY scale vector and external control to step size (FRAC)
Set up new guess vector by using saved guess vector VSAVE and DELTAV (increments and guess at a time)
STIRSM
B
C
H
I
J
K
F
G

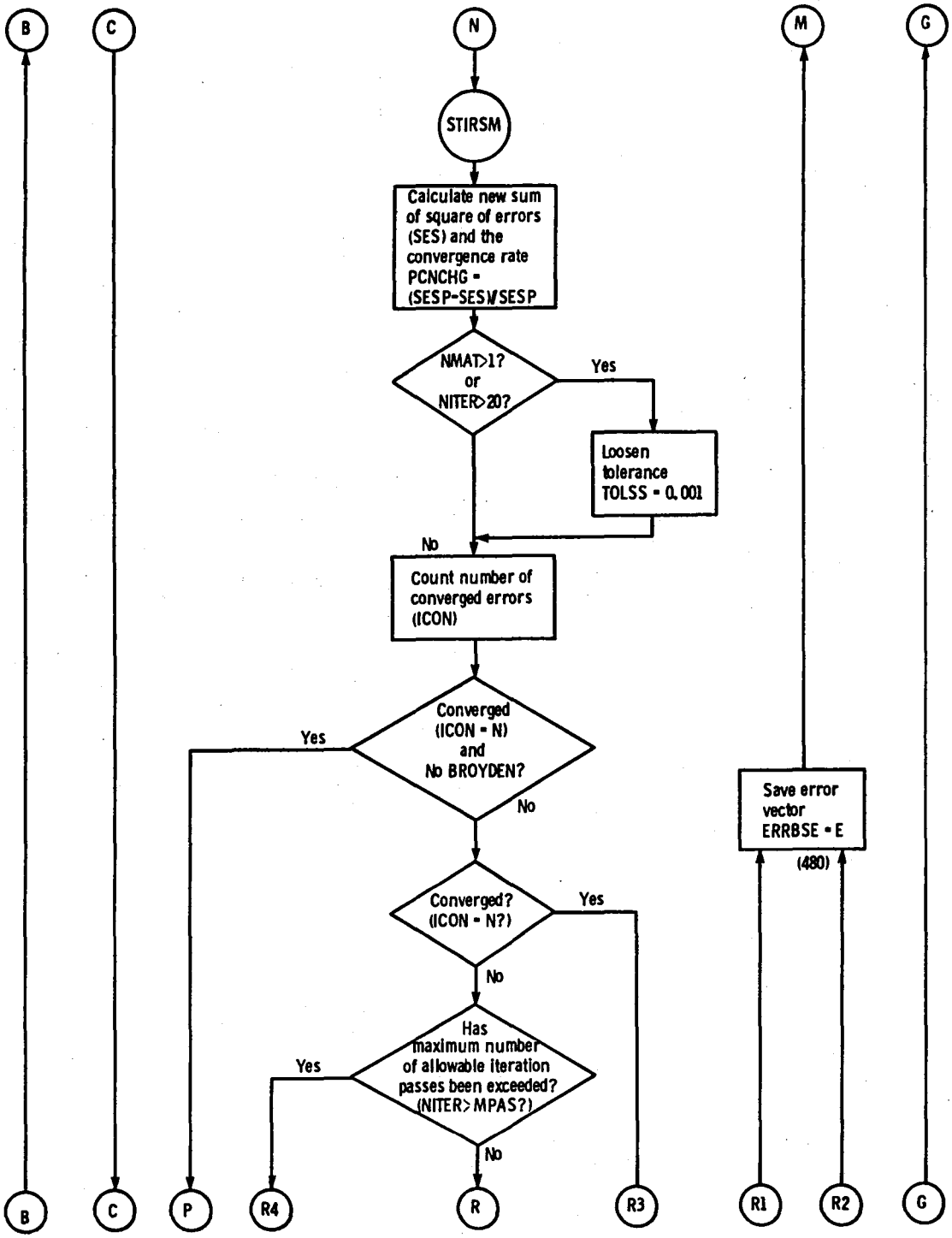
Subroutine INTEGR - Continued.



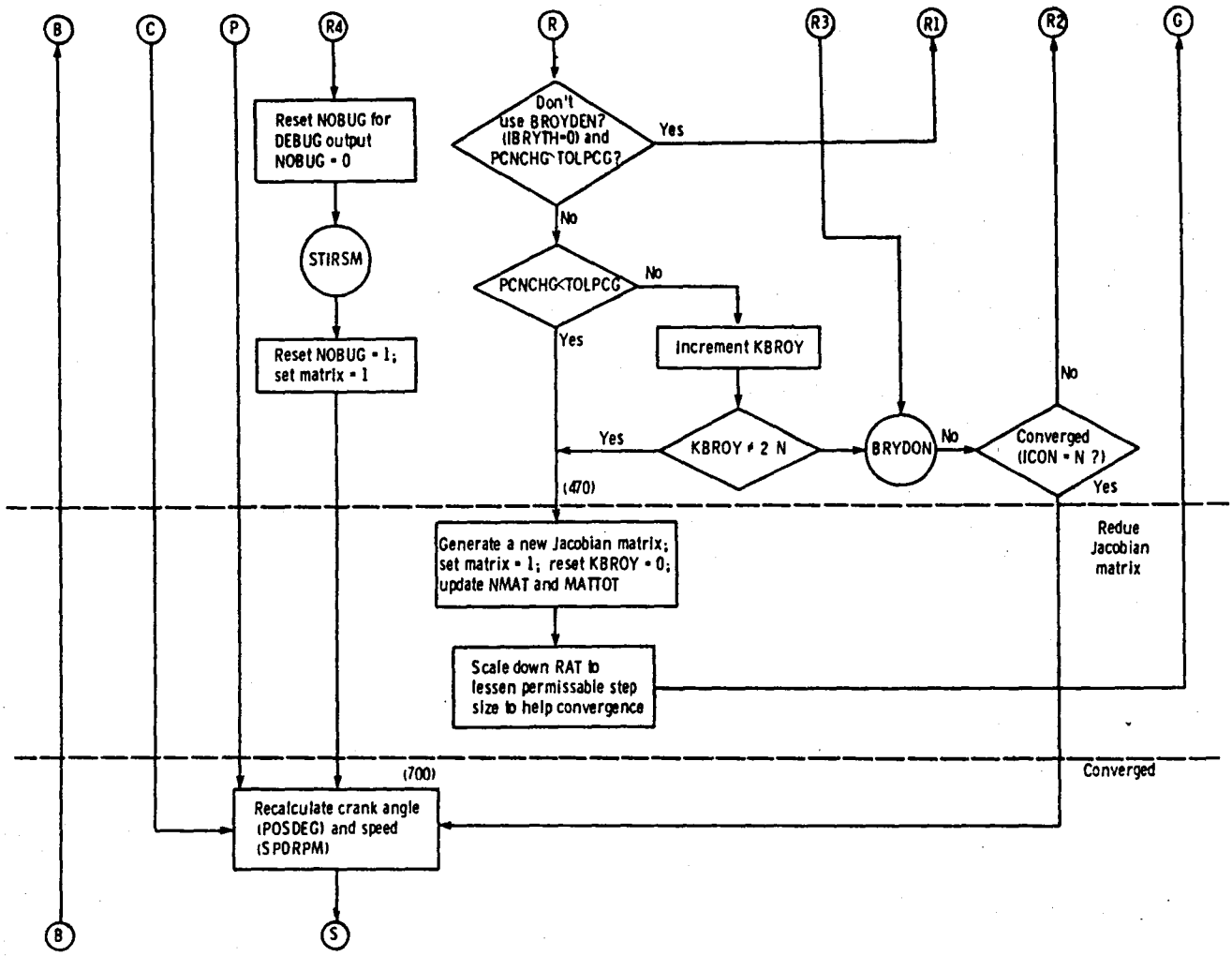
Subroutine INTEGR - Continued.



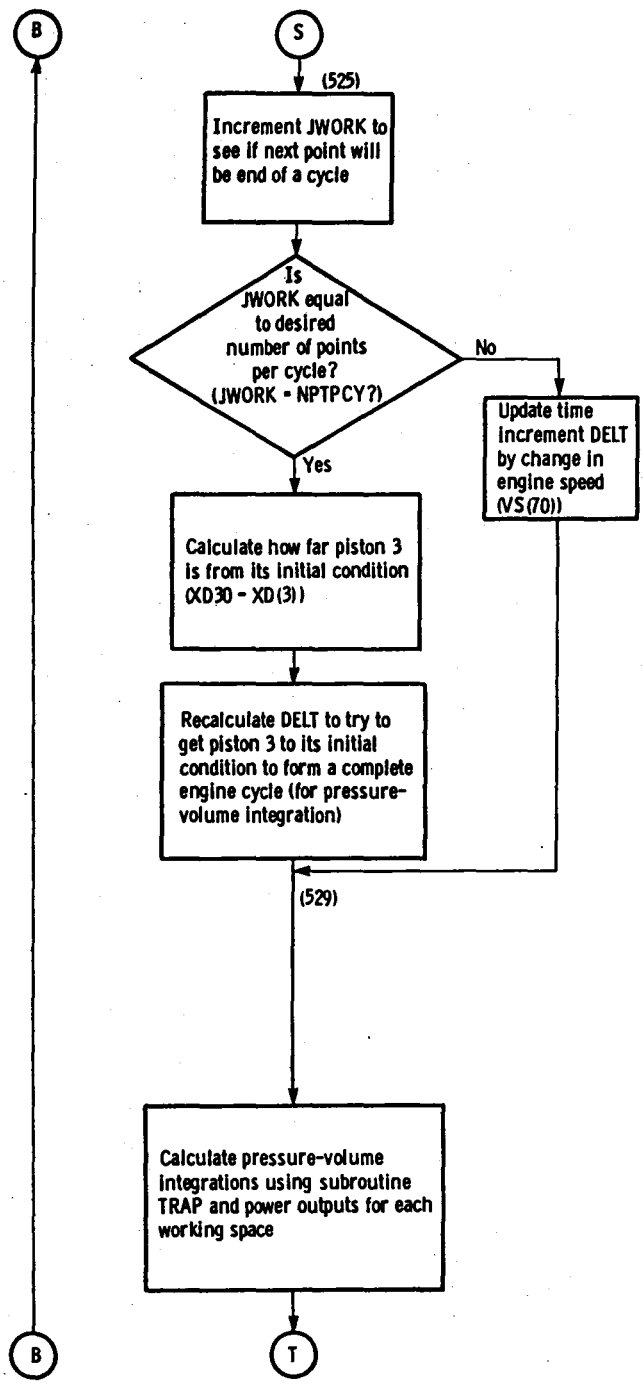
Subroutine INTEGR - Continued.



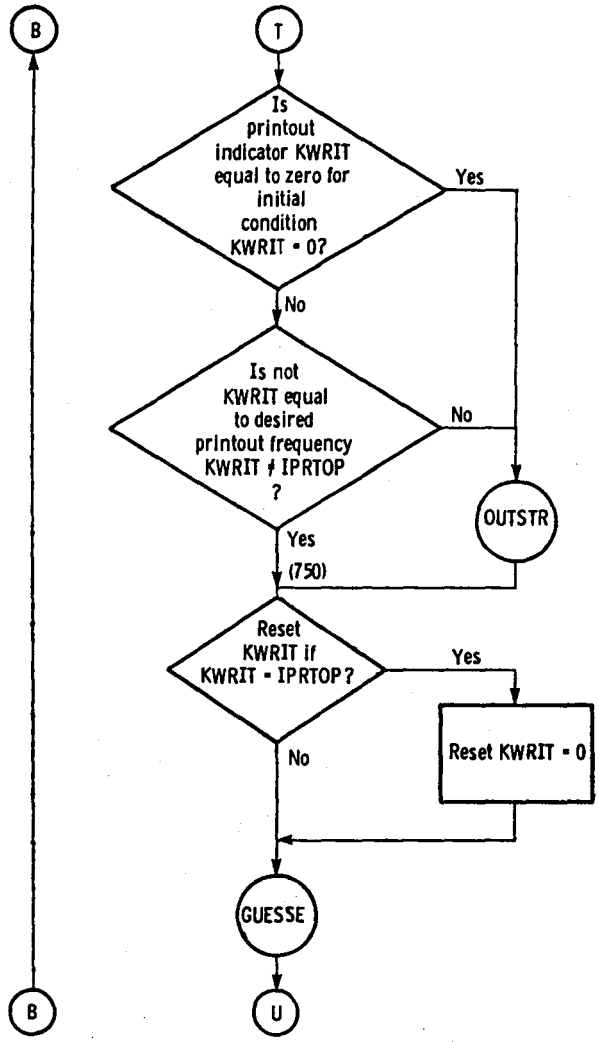
Subroutine INTEGR - Continued.

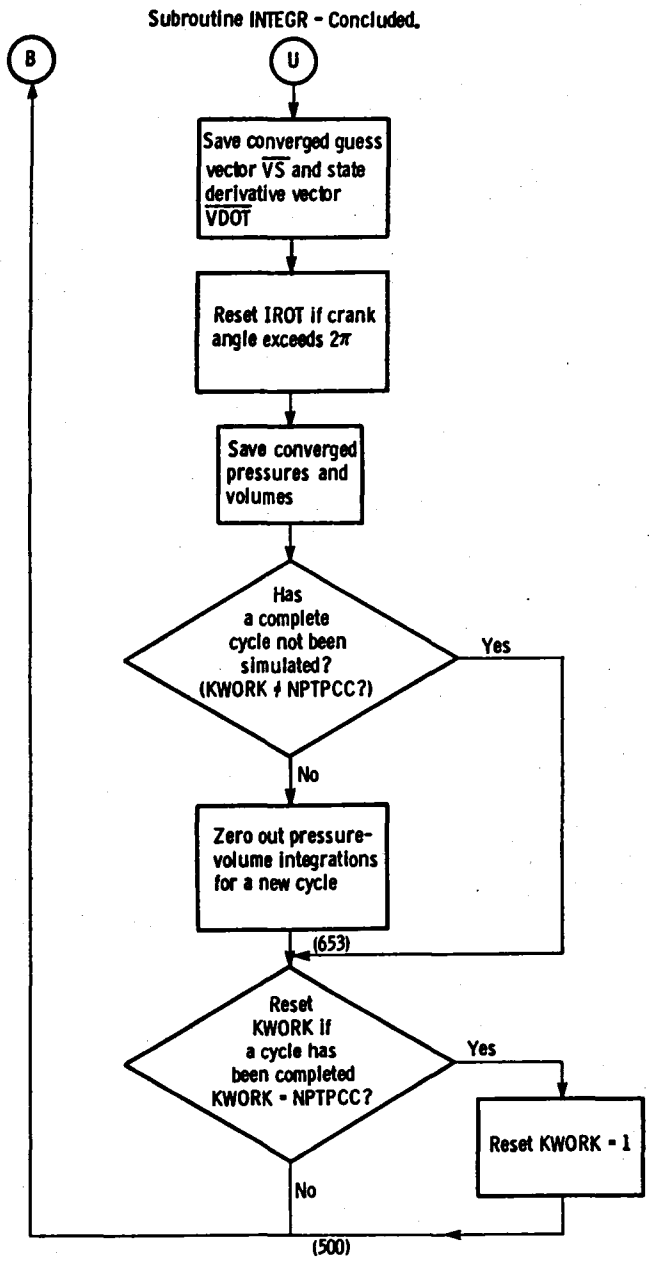


Subroutine INTEGR - Continued.

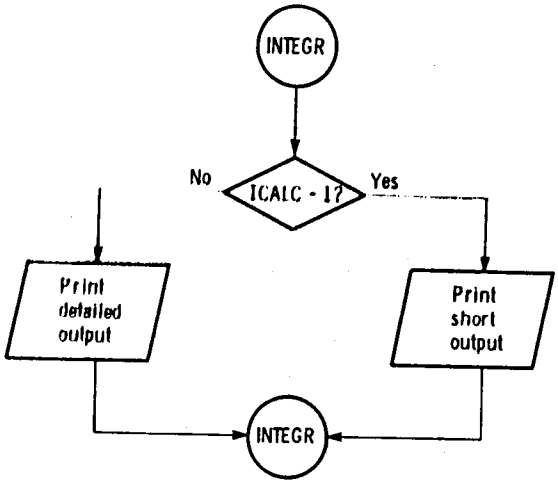


Subroutine INTEGR - Continued.

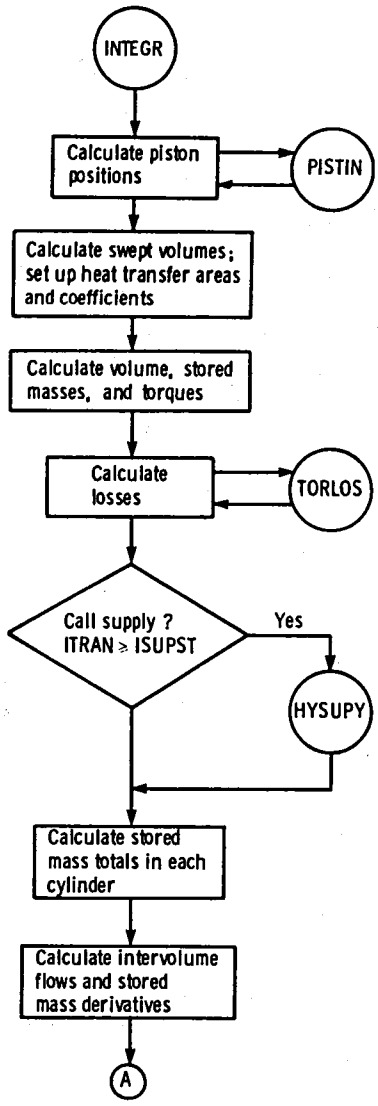



Subroutine INTEGR - Concluded.
B
U
Save converged guess vector VS and state derivative vector VDOT
Reset IROT if crank angle exceeds 2π
Save converged pressures and volumes
Has a complete cycle not been simulated? (KWORK ≠ NPTPCC?)
Yes
No
Zero out pressure-volume integrations for a new cycle
(653)
Reset KWORK if a cycle has been completed KWORK = NPTPCC?
Yes
Reset KWORK = 1
No
(500)

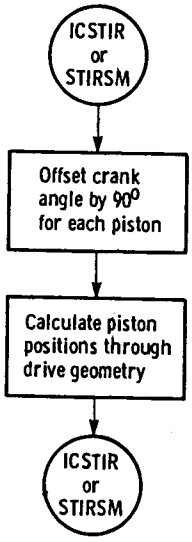
Subroutine OUTSTR



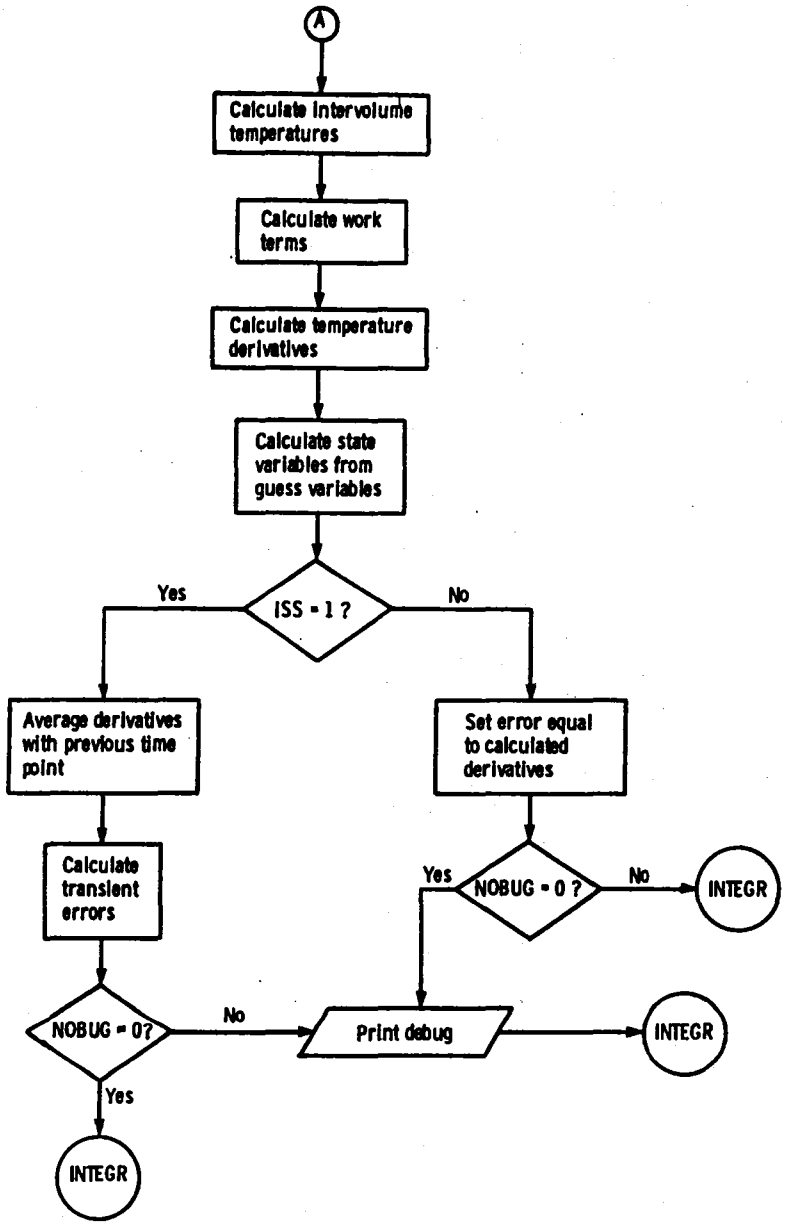
Subroutine STIRSM



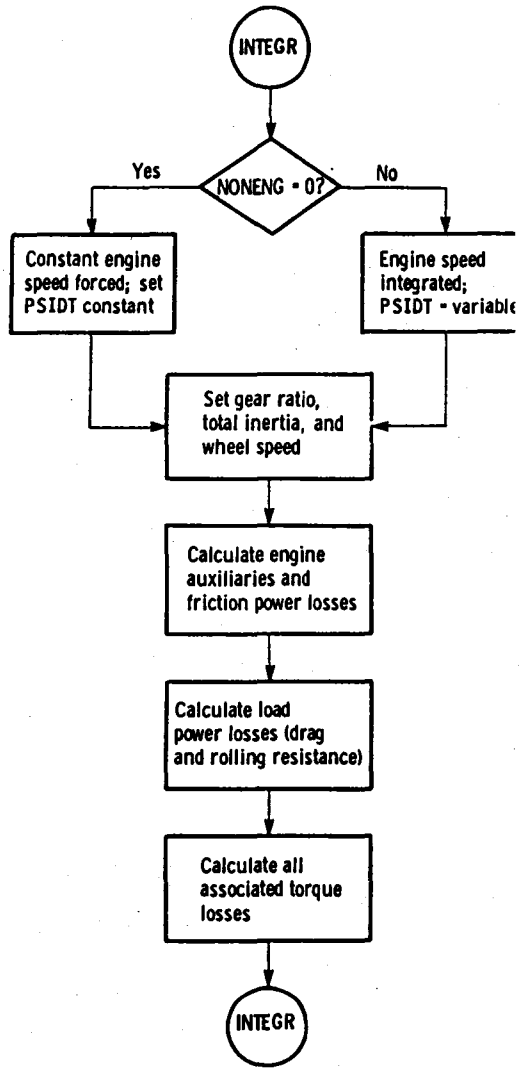
Subroutine PISTIN



Subroutine STIRSM. - Continued.



Subroutine TORLOS



Subroutine TRAP

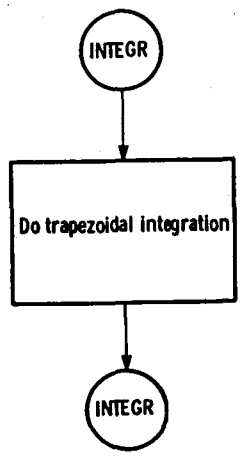


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TABLE I. - PROGRAM INPUT: ENGINE GEOMETRY

Name	Setting	Description
AD	23.7613	Piston area
AE	1.1290	Piston rod area
RODL	10.0	Crank rod length
VR[a]	115.332	Regeneration volume
VOE	11.459	Expansion space dead volume
VOC	32.5939	Compression space dead volume
VH	52.4058	Heater volume
VCOLD	29.2378	Cooler volume
STROKE	4.0	Piston strike
ALPHA	90.0	Crank angle lag

[a]Excludes mesh volume.

TABLE II. - PROGRAM INPUT: HEATER DATA

Name	Setting	Description
HH	71.4061	Heater heat transfer coefficient
AWH	426.9669	Heater heat transfer area
TWH	705.0	Heater wall temperature

TABLE III. - PROGRAM INPUT: COOLER DATA

Name	Setting	Description
HC	51.8739	Cooler heat transfer coefficient
AWC	804.1274	Cooler heat transfer area
TWC	86.0	Cooler wall temperature

TABLE IV. - PROGRAM SETUP: REGENERATOR DATA

Name	Setting	Description
HR	168.9762	Regenerator heat transfer coefficient
AWR	66870.834	Regenerator heat transfer area
CVM	142.1345	Specific heat of the mesh
WSM	0.6523	Mass of the mesh

TABLE V. - PROGRAM SETUP: GAS TEMPERATURE DISTRIBUTION GUESS

Name	Setting	Description
TEO	624.44	Expansion space temperature
THO	632.78	Heater temperature
TR1O	505.56	1st regenerator segment temperature
TR2O	360.0	2nd regenerator segment temperature
TR3O	214.44	3rd regenerator segment temperature
TCOLDO	105.0	Cooler temperature
TCO	105.0	Compression space temperature

TABLE VI. - PROGRAM SETUP: CONSTANTS

Name	Setting	Function
RANK	273.0	Converts centigrade to kelvin
DEGR	57.296	Converts degree to radians
PIE	3.1416	- - - - - - - - - - - - - -
R	4125.6	Gas constant
G	10017.0	Gravitational constant
AJ	1.0	Mechanical equivalent of heat

TABLE VII. - PROGRAM INPUT: FLOW RESISTANCES BETWEEN VOLUMES

Name	Setting	Description
RST(1)	0.38010	Resistance between expansion space and heater
RST(2)	0.76020	resistance between heater and 1st regenerator segments
RST(3)	0.76020	resistance between 1st regenerator and 2nd regenerator segments
RST(4)	0.76020	resistance between 2nd regenerator and 3rd regenerator segments
RST(5)	0.76020	resistance between 3rd regenerator segment and cooler
RST(6)	0.38010	resistance between cooler and compression space

TABLE VIII. - PROGRAM INPUT: HYDROGEN CONSTANTS

Name	Setting	Description
CP	1292.13	Gas constant
GAMMA	1.39	Gas constant

TABLE IX. - PROGRAM INPUT: MATRIX INPUT DATA

Name	Setting	Function
VDELTA	0.01	Perturb initial guesses by 1 percent
FRAC	1.0	External control of iteration step magnitude
TOL1	0.001	Lower limit on tolerance error for matrix linearity
TOL2	0.01	Upper limit on tolerance error for matrix linearity
TOLSS[a]	0.0001	Solution tolerance
N	68	System order NONENG = 0
	70	System order NONENG = 1
NTMAX	70	Largest system order
MPAS	50	Limits convergence failure to 50 passes
TOLPCG[b]	0.1	Recalculate Jacobian matrix when convergence rate (PCNCHG) falls below TOLPCG - no BROYDEN algorithm.

[a]If the number of iterations is greater than 20 or the number of matrices generated is greater than 1, TOLSS is set to 0.001 at that point.

[b]If BROYDEN is used, TOLPCG = 0.

TABLE X. - PROGRAM INPUTS: SWITCHS

Name	Setting	Function
ISS	0	Set up initial conditions
	1	Run transient (set internally in program)
ICALC	0	Detailed printout
	1	Shortened printout
MATRIX	1	If initial guesses do not converge the simulation, generates a Jacobian matrix
NONENG	0	Force crank angel as a function of time
	1	Run the simulation as an engine
IPRTOP	NN	Printout data every NN points
IBRYTH	0	Do not use BROYDEN update algorithm
	1	Use BROYDEN update algorithm
IHPCNV	0	Use logic in program to determine need for a new Jacobian matrix
	1	Generate a new Jacobian at every time point
NOBUG	0	No debut output
	1	Internally set to give a debug output when a convergence failure or matrix generation problem occurs

TABLE XI. - PROGRAM INPUT: RUN CONDITIONS

Name	Setting	Function
ALEAK	0	Piston rod leakage area
PSOURC	15.0	Hydrogen bottle source pressure
TSOURC	10.0	Hydrogen bottle source temperature
SPDRPM	2000	Desired engine speed
CYCLPR	5.0	Initial engine pressure
SPDMAX	4000	Maximum engine speed
CYCLPM	15.0	Maximum engine pressure
NCYSUP*	10	Start hydrogen supply
NCYSTP*	200	End hydrogen supply

[a]If no supply transient is desired, make NCYSUP and NCYSTP greater than NUMBCY.

TABLE XII. - PROGRAM INPUT: LOAD CONDITIONS

Name	Setting	Function
GTRAN	1.0/2.53	Transmission gear ratio
GR	1.5	Gear ratio
WTENG	0 kg	Engine mass
WTWHEL	29.48 kg	Mass of a wheel
WTCAR	1420 kg	Mass of a car
RWHEEL	30.48 cm	Tire wheel radius

TABLE XIII. - PROGRAM INPUT: CYCLE DATA

Name	Setting	Function
NPTPCY	200	Number of integration points/cycle
NUMBCY	3	Number of desired cycles

TABLE XIV. - SHORT PRINTOUT (ICALC = 1)

STIRLING ENGINE FOUR CYLINDER, SEVEN VOLUMES PER CYLINDER, CONTROLS MODEL

RUN CONDITIONS FOR THIS TRANSIENT

TWH =	978.3	TWC =	359.3	CYCLPR =	5.000	NONENG =	0
ALEAK =	0.0000	PSOURC =	10.00	TSOURC =	283.3	ISUPST =	2001

NUMBCY =	100		
ISPSTP =	40001		

TIME	POWERT	PFRICT	PAUX	PRRF	PDRAG	PLOAD	PENG	PNET	ITRAN	PAVEMP	
POSDEG	TORQT	TFRICT	TAUX	TRRF	TDRAG	TLOAD	TENG	TNET	KWORK	SPDRPM	VKPH

TABLE XV. - LONG PRINTOUT (ICALC = 0)

STIRLING ENGINE FOUR CYLINDER, SEVEN VOLUMES PER CYLINDER, CONTROLS MODEL

RUN CONDITIONS FOR THIS TRANSIENT

TWH = 978.3	TWC = 359.3	CYCLPR = 5.000	NONENG = 0	NUMBCY = 100	
ALEAK = 0.0000	PSOURC = 10.00	TSOURC = 283.3	ISUPST = 2001	ISPSTP = 40001	

TIME	XD1	XD2	XD3	XD4	POSDEG	SPDRPM	PAVEMP	WTOT	DELT	ITRAN
WSS1	PE1	PH1	PR11	PR21	PR31	PCOLD1	PC1	WT1	PWR1	TRQ1
WSSCN1	TE1	TH1	TR11	TR21	TR31	TCOLD1	TC1	TWR11	TWR21	TWR31
WSS2	PE2	PH2	PR12	PR22	PR32	PCOLD2	PC2	WT2	PWR2	TRQ2
WSSCN2	TE2	TH2	TR12	TR22	TR32	TCOLD2	TC2	TWR12	TWR22	TWR32
WSS3	PE3	PH3	PR13	PR23	PR33	PCOLD3	PC3	WT3	PWR3	TRQ3
WSSCN3	TE3	TH3	TR13	TR23	TR33	TCOLD3	TC3	TWR13	TWR23	TWR33
WSS4	PE4	PH4	PR14	PR24	PR34	PCOLD4	PC4	WT4	PWR4	TRQ4
WSSCN4	TE4	TH4	TR14	TR24	TR34	TCOLD4	TC4	TWR14	TWR24	TWR34

TIME	POWERT	PFRICT	PAUX	PRRF	PDRAG	PLOAD	PENG	PNET	ITRAN	PAVEMP	
POSDEG	TORQT	TFRICT	TAUX	TRRF	TDRAG	TLOAD	TENG	TNET	KWORK	SPDRPM	VKPH

TABLE XVI. - DEBUG PRINTOUT (FROM STIRSM)

I	VS	VCONV	VWS	VDOT	VDOTT	E
1	610.25000	0.15300290E-03	0.15981174E-03	-0.79999983E-01	-0.39999992E-01	-0.83716273E-01
2	608.25000	0.12455953E-03	0.12967623E-03	-0.19999981E-01	-0.99999905E-02	-0.53120777E-01
3	603.25000	0.10629979E-03	0.10975669E-03	0.19999981E-01	0.99999905E-02	-0.18409215E-01
4	599.25000	0.13073008E-03	0.13408644E-03	0.19999985E-01	0.99999905E-02	-0.14199920E-01
5	596.25000	0.16974067E-03	0.17322700E-03	0.00000000	0.00000000	-0.20539172E-01
6	593.25000	0.16643657E-03	0.16900044E-03	0.59999999E-01	0.29999997E-01	0.11632819E-01
7	593.25000	0.70013548E-03	0.71092020E-03	0.00000000	0.00000000	-0.15403751E-01
8	1616.0000	1616.0000	1616.0000	-315490.56	-157745.25	-0.14642194E-01
9	1631.0000	1631.0000	1631.0000	164707.06	82353.500	0.75738952E-02
10	1402.0000	1402.0000	1402.0000	358807.81	179403.88	0.19194424E-01
11	1140.0000	1140.0000	1140.0000	259640.13	129820.06	0.17081585E-01
12	878.00000	878.00000	878.00000	126617.88	63308.938	0.10815877E-01
13	681.00000	681.00000	681.00000	87375.000	43687.500	0.96227974E-02
14	681.00000	681.00000	681.00000	0.00000000	0.00000000	0.00000000
15	1402.0000	1402.0000	1402.0000	0.00000000	0.00000000	0.00000000
16	1140.0000	1140.0000	1140.0000	0.00000000	0.00000000	0.00000000
17	878.00000	878.00000	878.00000	0.00000000	0.00000000	0.00000000
18	650.55054	0.28928765E-03	0.28447737E-03	-0.39999999E-01	-0.20000000E-01	0.62577166E-02
19	649.55054	0.14103967E-03	0.10972896E-03	0.00000000	0.00000000	0.22199923
20	647.55054	0.12036404E-03	0.11781685E-03	-0.20000000E-01	-0.99999979E-02	0.87002441E-02
21	644.55054	0.14802665E-03	0.14422277E-03	-0.39999966E-01	-0.19999981E-01	0.54306947E-02
22	639.55054	0.19219861E-03	0.18580700E-03	-0.40000021E-01	-0.20000011E-01	0.17646361E-01
23	632.55054	0.18845737E-03	0.18019609E-03	-0.99999964E-01	-0.49999982E-01	0.40395558E-02
24	626.55054	0.47153048E-03	0.44658361E-03	0.23999995	0.11999995	0.91079712E-01
25	1616.0000	1616.0000	1616.0000	-88617.063	-44308.531	-0.41127950E-02
26	2058.3733	1631.0000	2058.3733	-550383.81	-275191.88	-0.28734016
27	1402.0000	1402.0000	1402.0000	244696.00	122348.00	0.13090003E-01
28	1140.0000	1140.0000	1140.0000	73770.188	36885.094	0.48533008E-02
29	878.00000	878.00000	878.00000	157733.63	78866.813	0.13473827E-01
30	681.00000	681.00000	681.00000	-104422.56	-52211.281	-0.11500280E-01
31	681.00000	681.00000	681.00000	142731.19	71365.563	0.15719287E-01
32	1402.0000	1402.0000	1402.0000	0.00000000	0.00000000	0.00000000
33	1140.0000	1140.0000	1140.0000	0.00000000	0.00000000	0.00000000
34	878.00000	878.00000	878.00000	0.00000000	0.00000000	0.00000000
35	833.99536	0.22913910E-03	0.21840225E-03	0.15999997	0.79999983E-01	0.99227250E-01
36	837.99536	0.18654518E-03	0.17865693E-03	-0.40000021E-01	-0.20000011E-01	0.26204064E-01
37	843.99536	0.15919868E-03	0.15355846E-03	-0.19999981E-01	-0.99999905E-02	0.26006632E-01
38	848.99536	0.19578644E-03	0.18996875E-03	-0.19999981E-01	-0.99999905E-02	0.22053093E-01
39	852.99536	0.25421008E-03	0.24781842E-03	-0.39999984E-01	-0.19999992E-01	0.13341986E-01
40	854.99536	0.24926174E-03	0.24356444E-03	-0.39999999E-01	-0.20000000E-01	0.10821126E-01
41	854.99536	0.27676346E-03	0.27043745E-03	0.00000000	0.00000000	0.22857092E-01
42	1616.0000	1616.0000	1616.0000	476983.13	238491.56	0.22137206E-01
43	1631.0000	1631.0000	1631.0000	-134883.63	-67441.813	-0.62024966E-02
44	1402.0000	1402.0000	1402.0000	-331204.94	-165602.44	-0.17717805E-01
45	1140.0000	1140.0000	1140.0000	-218314.31	-109157.13	-0.14362775E-01
46	878.00000	878.00000	878.00000	-127025.94	-63512.969	-0.10850735E-01
47	681.00000	681.00000	681.00000	-101612.81	-50806.406	-0.11190835E-01
48	681.00000	681.00000	681.00000	0.00000000	0.00000000	0.00000000
49	1402.0000	1402.0000	1402.0000	0.00000000	0.00000000	0.00000000
50	1140.0000	1140.0000	1140.0000	0.00000000	0.00000000	0.00000000
51	878.00000	878.00000	878.00000	0.00000000	0.00000000	0.00000000
52	817.66260	0.37334496E-04	0.38463462E-04	0.00000000	0.00000000	-0.30239236E-01
53	817.66260	0.16920538E-03	0.17432208E-03	0.39999999E-01	0.20000000E-01	-0.12509651E-01
54	819.66260	0.14440081E-03	0.14913132E-03	0.20000000E-01	0.99999979E-02	-0.22371810E-01
55	822.66260	0.17758766E-03	0.18407662E-03	0.39999966E-01	0.19999981E-01	-0.19646429E-01
56	827.66260	0.23058079E-03	0.24045871E-03	0.79999983E-01	0.39999992E-01	-0.16818088E-01
57	836.66260	0.22609244E-03	0.23834192E-03	0.60000002E-01	0.30000001E-01	-0.34275722E-01
58	842.66260	0.56570349E-03	0.60062949E-03	-0.23999995	-0.11999995	-0.93557775E-01
59	1616.0000	1616.0000	1616.0000	0.00000000	0.00000000	0.00000000
60	1631.0000	1631.0000	1631.0000	220892.44	110446.19	0.10157526E-01
61	1402.0000	1402.0000	1402.0000	-56801.113	-28400.555	-0.30385756E-02
62	1140.0000	1140.0000	1140.0000	-58973.547	-29486.773	-0.38798389E-02
63	878.00000	878.00000	878.00000	-39558.840	-19779.418	-0.33791710E-02
64	681.00000	681.00000	681.00000	-87399.125	-43699.563	-0.96254535E-02
65	681.00000	681.00000	681.00000	-106124.31	-53062.156	-0.11687700E-01
66	1402.0000	1402.0000	1402.0000	0.00000000	0.00000000	0.00000000
67	1140.0000	1140.0000	1140.0000	0.00000000	0.00000000	0.00000000
68	878.00000	878.00000	878.00000	0.00000000	0.00000000	0.00000000
69	4.7123709	4.7123709	4.7123709	209.43994	104.71997	0.33333530E-02
70	209.43994	209.43994	209.43994	-4.4528265	-2.2264128	-0.15945461E-05

TABLE XVII. - INPUT FOR SUPPLY TEST CASE (MAINST)

```
      COMMON/TEMINT/TPRM(24)
      COMMON/STEPIT/FREQQ,FREQ
      COMMON/SUPLY/WSS(4),NONENG,PSOURC,TSOURC,WSSCN(4),ALEAK
      COMMON/PCBARR/PC1MAX,PC2MAX,PC3MAX,PC4MAX,PC1MIN,PC2MIN,PC3MIN,
     1PC4MIN
      COMMON/ITCONV/VS(70),E(70),DELTAV(70),VSAVE(70),XD(4),
     1VDOTSV(70),XDCNV(4)
      COMMON/PIN/AD,AR,G,HH,HR,HC,AWH,AWR,AWC,AJ,CV,GAMMA,CVM,WSM,R,
     1RST(6),VH,VR,VCOLD,WTOTT(4),WTOT,WTOTSV,
     2       RD,TOLSS,TOL2,TOL1,TOLDY,ISS,DELT,N,NMAX,VOE,VOC
     3,VTOT1,TWC,TWH,RODL
      COMMON/POWER/XDD(4),PINST,AMPLIT,TIME,OMEGA,ALPHA,XDDCNV(4),PSI
      COMMON/SAVIT/VCONV(70),VDOT(70),VGUESS(70),NOBUG
     1,VWS(70),VNIM(70),VDOTT(70)
      COMMON/ANGLS/SIN1(4),COS1(4),SIN11(4),TORQ(4),TORQT
      COMMON/PRTIT/VE1(4),VC1(4)
      COMMON/TEMPSO/TEO,THO,TR1O,TR2O,TR3O,TCOLDO,TCO,TWR1O,TWR2O,TWR3O
      COMMON/CARLOD/GTRAN,GR,AIE,AIWHEL,AIVEH,RWHEEL,AINERT
      COMMON/CONST/PIE,DEGR,RANK
      COMMON/SWITCH/ISUPST,ICALC,MATRIX,IPRTOP,IBRYTH,IHPCNV,ISPSTP
      COMMON/CYDATA/NPTPCY,ITRMAX,NUMBCY,STROKE,CYCLPR,SPDRPM,POSDEO
      COMMON/OUTPR/PCMAX,PCMIN,PEMAX,PEMIN,PAVEMP,KWORK
      COMMON/MOVIT/DELPSI,FRAC,VDELTA,REF,MPAS,POSDEG,TOLPCG
C
C        ENGINE GEOMETRY
C
      AD=23.7613
      AR=1.1290
      RODL=10.0
      VR=115.332
      VOE=11.459
      VOC=32.5939
      VH=52.4058
      VCOLD=29.2378
      STROKE=4.0
      ALPHA=90.0
C
C        HEATER
C
      HH=71.4061
      AWH=426.9669
      TWH=705.0
C
C        COOLER
C
      HC=51.8739
      AWC=804.1274
      TWC=86.0
C
C        REGENERATOR
C
      HR=168.9762
      AWR=66870.834
      CVM=142.1345
      WSM=.6523
C
C        TEMPERATURE DISTRIBUTION
C
      TEO=624.44
      THO=632.7778
      TR1O=505.5556
      TR2O=360.0
      TR3O=214.44
      TCOLDO=105.0
      TCO=105.0
C
C        CONSTANTS
C
      RANK=273.0
      DEGR=57.296
      PIE=3.1416
      R=4125.6
      G=10017.0
      AJ=1.0
```

TABLE XVII. - Continued.

```
 7500  C
 7600  C        FLOW RESISTANCES BETWEEN VOLUMES
 7700  C
 7800        RST(1)=.38010
 7900        RST(2)=.76020
 8000        RST(3)=.76020
 8100        RST(4)=.76020
 8200        RST(5)=.76020
 8300        RST(6)=.38010
 8400  C
 8500  C        HYDROGEN CONSTANTS
 8600  C
 8700        CP=1292.13
 8800        GAMMA=1.39
 8900  C
 9000  C        MATRIX INPUT DATA
 9100  C
 9200        VDELTA=.01
 9300        FRAC=1.0
 9400        TOL1=.001
 9500        TOL2=.01
 9600        TOLSS=.0001
 9700        N=70
 9800        NTMAX=70
 9900        MPAS=50
10000        TOLPCG=.1
10100  C
10200  C        SWITCHS
10300  C
10400        ICALC=1
10500        NONENG=1
10600        IPRTOP=200
10700        IBRYTH=1
10800        IMPCNV=0
10900        NOBUG=1
11000  C
11100  C        RUN CONDITIONS
11200  C
11300        PSOURC=10.0
11400        TSOURC=10.0
11500        ALEAK=0.0
11600        SPDRPM=2400.0
11700        CYCLPR=5.00
11800        SPDMAX=4000.
11900        CYCLPM=15.0
12000        POSDEO=270.0
12100        NCYSUP=10
12200        NCYSTP=200
12300  C
12400  C        LOAD CONDITIONS
12500  C
12600        GTRAN=1.0/2.53
12700        GR=1.5
12800        WTENG=0.0
12900        WTWHEL=29.48
13000        WTCAR=1420.0
13100        RWHEEL=30.48
13200  C
13300  C        CYCLE DATA
13400  C
13500        NPTPCY=200
13600        NUMBCY=100
13700  C
13800  C        CALCULATED INPUT
13900  C
14000        IF (NONENG .EQ. 0) N=68
14100        IF (IBRYTH .EQ. 1) TOLPCG=0.0
14200        REF=(TOL1+TOL2)/2.0
14300        ITRMAX=NPTPCY*NUMBCY+1
14400        ISUPST=NCYSUP*NPTPCY+1
14500        ISPSTP=NCYSTP*NPTPCY+1
14600        RANK=RANK*460.0/273.0
```

TABLE XVII. - Concluded.

```
14700         AIE=0.0
14800         WTWHEL=WTWHEL/4.0
14900         RWHELM=RWHEEL/100.0
15000         AIWHEL=(WTWHEL/2.0)*(RWHELM**2+(RWHELM/2.0)**2)
15100         AIVEH=WTCAR*RWHELM**2
15200         AIWHEL=AIWHEL*60.56/.4279
15300         AIVEH=AIVEH*1166.56/131.9223
15400         RWHEEL=RWHEEL*1.0/30.48
15500         CMIN=2.54
15600         CMINS=CMIN*2.54
15700         CMINC=CMINS*2.54
15800         AD=AD/CMINS
15900         AR=AR/CMINS
16000         VR=VR/CMINC
16100         VOE=VOE/CMINC
16200         VH=VH/CMINC
16300         VCOLD=VCOLD/CMINC
16400         VOC=VOC/CMINC
16500         RODL=RODL/CMIN
16600         STROKE=STROKE/CMIN
16700         TWH=1.8*(TWH+40.)-40.
16800         TWC=1.8*(TWC+40.)-40.
16900         AWH=AWH/CMINS
17000         AWC=AWC/CMINS
17100         AWR=AWR/CMINS
17200         WSM=WSM/.4536
17300         HH=HH*.786/71.4061
17400         HR=HR*1.861/168.9762
17500         HC=HC*.571/51.8739
17600         TEO=1.8*(TEO+40.)-40.
17700         THO=1.8*(THO+40.)-40.
17800         TR1O=1.8*(TR1O+40.)-40.
17900         TR2O=1.8*(TR2O+40.)-40.
18000         TR3O=1.8*(TR3O+40.)-40.
18100         TCOLDO=1.8*(TCOLDO+40.)-40.
18200         TCO=1.8*(TCO+40.)-40.
18300         AJ=AJ*9337.92
18400         G=G*386.4/10017.
18500         R=R*9197./4125.6
18600         RST(1)=RST(1)*25./.38010
18700         RST(6)=RST(6)*25./.38010
18800         DO 1 I=2,5
18900         RST(I)=RST(I)*50./.76020
19000       1 CONTINUE
19100         CP=CP*3.4838/1292.13
19200         CV=CP/GAMMA
19300         PSOURC=PSOURC*2175./15.
19400         TSOURC=1.8*(TSOURC+40.)-40.
19500         ALEAK=ALEAK*.5/3.2258
19600         CYCLPR=CYCLPR*2175./15.
19700         CYCLPM=CYCLPM*2175./15.
19800         CVM=CVM*.11/142.1345
19900         TWR1O=TR1O
20000         TWR2O=TR2O
20100         TWR3O=TR3O
20200         ISS=0
20300         MATRIX=1
20400         CALL ICSTIR
20500         STOP
20600         END
```

TABLE XVIII. - TEST CASE PRINTOUT

STIRLING ENGINE FOUR CYLINDER, SEVEN VOLUMES PER CYLINDER, CONTROLS MODEL

RUN CONDITIONS FOR THIS TRANSIENT

TWH = 978.3 TWC = 359.3 CYCLPR = 5.000 NONENG = 1 NUMBCY = 100
ALEAK = 0.0000 PSOURC = 10.00 TSOURC = 283.3 ISUPST = 2001 ISPSTP = 40001

TIME / POSDEG	POWERT / TORQT	PFRICT / TFRICT	PAUX / TAUX	PRRF / TRRF	PDRAG / TDRAG	PLOAD / TLOAD	PENG / TENG	PNET / TNET	ITRAN / KWORK	PAVEMP / SPDRPM	VKPH
0.0000	0.0000	3.849	2.627	3.036	4.078	7.113	6.475	-13.59	1	4.028	
270.0	54.00	15.32	10.45	12.09	16.22	28.31	25.77	-0.8228E-01	1	2400.	72.65
0.2506E-01	13.38	3.848	2.627	3.036	4.077	7.113	6.474	-0.2111	201	5.064	
270.0	52.68	15.31	10.45	12.09	16.22	28.31	25.76	-1.391	201	2400.	72.65
0.5006E-01	13.97	3.843	2.627	3.036	4.078	7.113	6.470	0.3847	401	5.008	
270.0	53.67	15.29	10.45	12.09	16.22	28.31	25.75	-0.3830	201	2400.	72.65
0.7506E-01	14.13	3.843	2.627	3.036	4.078	7.114	6.469	0.5485	601	4.992	
270.0	53.97	15.29	10.45	12.09	16.22	28.31	25.74	-0.8242E-01	201	2400.	72.65
0.1001	14.18	3.841	2.627	3.036	4.078	7.114	6.468	0.6011	801	4.987	
270.0	54.06	15.29	10.45	12.09	16.23	28.31	25.74	0.1142E-01	201	2400.	72.66
0.1251	14.21	3.847	2.627	3.036	4.078	7.114	6.473	0.6196	1001	4.987	
270.0	54.14	15.31	10.45	12.09	16.23	28.31	25.76	0.6772E-01	201	2400.	72.66
0.1501	14.22	3.844	2.627	3.036	4.079	7.115	6.471	0.6307	1201	4.987	
270.0	54.14	15.30	10.45	12.09	16.23	28.31	25.75	0.7914E-01	201	2400.	72.66
0.1750	14.22	3.843	2.627	3.036	4.079	7.115	6.470	0.6392	1401	4.988	
270.0	54.21	15.29	10.45	12.09	16.23	28.31	25.74	0.1560	201	2400.	72.66
0.2000	14.23	3.843	2.627	3.036	4.079	7.115	6.470	0.6447	1601	4.989	
270.0	54.21	15.29	10.45	12.09	16.23	28.31	25.74	0.1513	201	2400.	72.66
0.2250	14.24	3.846	2.627	3.036	4.079	7.116	6.473	0.6480	1801	4.990	
270.0	54.22	15.30	10.45	12.09	16.23	28.32	25.76	0.1458	201	2400.	72.66

TABLE XVIII. - Continued.

0.2500	14.24	3.845	2.627	3.036	4.080	7.116	6.473	0.6514	2001	4.991	
270.0	54.28	15.30	10.45	12.09	16.23	28.32	25.75	0.2066	201	2400.	72.66
0.2750	14.78	3.858	2.627	3.036	4.080	7.117	6.486	1.177	2201	5.028	
270.0	55.28	15.35	10.45	12.09	16.23	28.32	25.80	1.156	201	2400.	72.67
0.3000	15.09	3.889	2.628	3.037	4.081	7.117	6.517	1.458	2401	5.112	
270.0	56.17	15.47	10.45	12.09	16.23	28.32	25.93	1.922	201	2401.	72.67
0.3250	15.34	3.922	2.628	3.037	4.082	7.118	6.550	1.671	2601	5.199	
270.0	56.99	15.60	10.45	12.09	16.23	28.32	26.06	2.614	201	2401.	72.68
0.3499	15.56	3.958	2.628	3.037	4.082	7.119	6.586	1.858	2801	5.285	
270.0	57.82	15.75	10.45	12.09	16.24	28.32	26.20	3.295	201	2401.	72.68
0.3749	15.78	3.992	2.629	3.037	4.083	7.121	6.621	2.035	3001	5.370	
270.0	58.62	15.88	10.45	12.09	16.24	28.33	26.33	3.959	201	2401.	72.69
0.3999	15.98	4.023	2.629	3.037	4.084	7.122	6.652	2.206	3201	5.453	
270.0	59.41	16.00	10.46	12.09	16.24	28.33	26.46	4.628	201	2401.	72.69
0.4249	16.18	4.058	2.629	3.038	4.086	7.123	6.688	2.366	3401	5.534	
270.0	60.20	16.14	10.46	12.09	16.25	28.33	26.60	5.268	201	2402.	72.70
0.4499	16.37	4.086	2.630	3.038	4.087	7.125	6.716	2.527	3601	5.612	
270.0	60.94	16.25	10.46	12.09	16.25	28.33	26.71	5.895	201	2402.	72.71
0.4748	16.55	4.116	2.630	3.038	4.088	7.127	6.746	2.682	3801	5.688	
270.0	61.65	16.36	10.46	12.09	16.25	28.34	26.82	6.490	201	2402.	72.71
0.4998	16.74	4.144	2.630	3.039	4.089	7.128	6.774	2.833	4001	5.763	
270.0	62.33	16.47	10.46	12.09	16.26	28.34	26.93	7.061	201	2402.	72.72
0.5248	16.91	4.171	2.631	3.039	4.091	7.130	6.802	2.974	4201	5.834	
270.0	63.00	16.58	10.46	12.09	16.26	28.35	27.04	7.613	201	2403.	72.73
0.5497	17.08	4.200	2.631	3.039	4.092	7.132	6.831	3.114	4401	5.904	
270.0	63.68	16.69	10.46	12.09	16.26	28.35	27.15	8.176	201	2403.	72.74
0.5747	17.24	4.228	2.632	3.040	4.094	7.134	6.860	3.246	4601	5.972	
270.0	64.32	16.80	10.46	12.09	16.27	28.35	27.26	8.701	201	2403.	72.75
0.5997	17.40	4.253	2.632	3.040	4.096	7.136	6.885	3.378	4801	6.038	
270.0	64.95	16.90	10.46	12.09	16.27	28.36	27.36	9.232	201	2404.	72.76

TABLE XVIII. - Continued.

0.6246	17.56	4.278	2.633	3.041	4.097	7.138	6.911	3.508	5001	6.103	
270.0	65.52	17.00	10.46	12.09	16.28	28.36	27.46	9.699	201	2404.	72.77
0.6496	17.71	4.303	2.633	3.041	4.099	7.140	6.936	3.630	5201	6.165	
270.0	66.10	17.09	10.46	12.09	16.28	28.37	27.55	10.18	201	2404.	72.78
0.6745	17.85	4.329	2.634	3.042	4.101	7.143	6.963	3.748	5401	6.226	
270.0	66.71	17.19	10.46	12.09	16.29	28.37	27.66	10.69	201	2405.	72.79
0.6995	17.99	4.353	2.634	3.042	4.103	7.145	6.987	3.861	5601	6.285	
270.0	67.30	17.28	10.46	12.09	16.29	28.38	27.75	11.17	201	2405.	72.80
0.7244	18.13	4.378	2.635	3.043	4.105	7.147	7.013	3.974	5801	6.342	
270.0	67.82	17.38	10.46	12.09	16.30	28.38	27.85	11.59	201	2405.	72.81
0.7493	18.26	4.396	2.636	3.043	4.107	7.150	7.032	4.081	6001	6.398	
270.0	68.33	17.45	10.46	12.09	16.30	28.39	27.92	12.03	201	2406.	72.83
0.7743	18.39	4.418	2.636	3.044	4.109	7.152	7.054	4.188	6201	6.452	
270.0	68.83	17.54	10.46	12.09	16.31	28.39	28.00	12.43	201	2406.	72.84
0.7992	18.52	4.445	2.637	3.044	4.111	7.155	7.082	4.284	6401	6.505	
270.0	69.32	17.64	10.46	12.09	16.31	28.40	28.10	12.81	201	2407.	72.85
0.8241	18.64	4.461	2.638	3.045	4.113	7.158	7.098	4.388	6601	6.556	
270.0	69.82	17.70	10.47	12.09	16.32	28.40	28.17	13.25	201	2407.	72.86
0.8491	18.76	4.481	2.638	3.045	4.115	7.161	7.119	4.482	6801	6.605	
270.0	70.28	17.78	10.47	12.09	16.32	28.41	28.24	13.62	201	2407.	72.88
0.8740	18.88	4.504	2.639	3.046	4.118	7.163	7.143	4.570	7001	6.654	
270.0	70.69	17.86	10.47	12.09	16.33	28.42	28.33	13.94	201	2408.	72.89
0.8989	18.99	4.519	2.640	3.046	4.120	7.166	7.159	4.667	7201	6.701	
270.0	71.10	17.92	10.47	12.09	16.34	28.42	28.39	14.29	201	2408.	72.90
0.9238	19.10	4.538	2.640	3.047	4.122	7.169	7.179	4.750	7401	6.747	
270.0	71.54	17.99	10.47	12.09	16.34	28.43	28.46	14.64	201	2409.	72.92
0.9487	19.20	4.556	2.641	3.047	4.125	7.172	7.198	4.832	7601	6.791	
270.0	71.90	18.06	10.47	12.09	16.35	28.44	28.53	14.93	201	2409.	72.93
0.9736	19.30	4.573	2.642	3.048	4.127	7.175	7.215	4.914	7801	6.835	
270.0	72.32	18.13	10.47	12.09	16.36	28.44	28.60	15.28	201	2410.	72.95

TABLE XVIII. - Continued.

0.9985	19.40	4.592	2.643	3.049	4.130	7.178	7.235	4.990	8001	6.876	
270.0	72.72	18.20	10.47	12.09	16.36	28.45	28.67	15.60	201	2410.	72.96
1.023	19.50	4.608	2.643	3.049	4.132	7.182	7.252	5.063	8201	6.917	
270.0	73.08	18.26	10.47	12.09	16.37	28.46	28.73	15.90	201	2411.	72.98
1.048	19.59	4.625	2.644	3.050	4.135	7.185	7.269	5.141	8401	6.957	
270.0	73.43	18.32	10.47	12.09	16.38	28.46	28.79	16.18	201	2411.	72.99
1.073	19.68	4.642	2.645	3.051	4.137	7.188	7.287	5.205	8601	6.995	
270.0	73.78	18.38	10.47	12.09	16.38	28.47	28.86	16.46	201	2412.	73.01
1.098	19.77	4.659	2.646	3.051	4.140	7.191	7.305	5.273	8801	7.033	
270.0	74.13	18.45	10.48	12.09	16.39	28.48	28.92	16.73	201	2412.	73.02
1.122	19.85	4.671	2.647	3.052	4.143	7.195	7.317	5.339	9001	7.069	
270.0	74.44	18.49	10.48	12.09	16.40	28.48	28.96	17.00	201	2413.	73.04
1.147	19.93	4.686	2.647	3.053	4.145	7.198	7.333	5.401	9201	7.104	
270.0	74.79	18.54	10.48	12.09	16.40	28.49	29.02	17.28	201	2413.	73.05
1.172	20.02	4.700	2.648	3.053	4.148	7.201	7.349	5.465	9401	7.138	
270.0	75.11	18.60	10.48	12.09	16.41	28.50	29.08	17.54	201	2414.	73.07
1.197	20.09	4.715	2.649	3.054	4.151	7.205	7.364	5.523	9601	7.171	
270.0	75.40	18.65	10.48	12.09	16.42	28.50	29.13	17.76	201	2414.	73.09
1.222	20.17	4.724	2.650	3.055	4.154	7.208	7.374	5.587	9801	7.204	
270.0	75.60	18.68	10.48	12.09	16.43	28.51	29.16	17.92	201	2415.	73.10
1.246	20.24	4.741	2.651	3.055	4.157	7.212	7.392	5.639	10001	7.236	
270.0	75.88	18.75	10.48	12.09	16.43	28.52	29.23	18.13	201	2415.	73.12
1.271	20.31	4.754	2.652	3.056	4.160	7.216	7.406	5.693	10201	7.266	
270.0	76.15	18.79	10.48	12.09	16.44	28.53	29.28	18.35	201	2416.	73.14
1.296	20.38	4.763	2.653	3.057	4.162	7.219	7.416	5.748	10401	7.296	
270.0	76.37	18.83	10.48	12.09	16.45	28.53	29.31	18.53	201	2417.	73.15
1.321	20.45	4.783	2.653	3.057	4.165	7.223	7.436	5.792	10601	7.325	
270.0	76.66	18.90	10.48	12.09	16.46	28.54	29.38	18.74	201	2417.	73.17
1.346	20.51	4.795	2.654	3.058	4.168	7.226	7.450	5.838	10801	7.353	
270.0	76.88	18.94	10.49	12.09	16.46	28.55	29.43	18.90	201	2418.	73.19

TABLE XVIII. - Concluded.

1.370	20.58	4.803	2.655	3.059	4.171	7.230	7.459	5.887	11001	7.381	
270.0	77.08	18.97	10.49	12.09	16.47	28.56	29.46	19.07	201	2418.	73.20
1.395	20.64	4.813	2.656	3.060	4.174	7.234	7.469	5.934	11201	7.408	
270.0	77.31	19.00	10.49	12.09	16.48	28.57	29.49	19.25	201	2419.	73.22
1.420	20.70	4.835	2.657	3.060	4.177	7.238	7.492	5.967	11401	7.433	
270.0	77.54	19.08	10.49	12.09	16.49	28.57	29.57	19.39	201	2419.	73.24
1.445	20.76	4.835	2.658	3.061	4.180	7.241	7.493	6.021	11601	7.458	
270.0	77.80	19.08	10.49	12.09	16.50	28.58	29.57	19.65	201	2420.	73.26
1.469	20.81	4.848	2.659	3.062	4.183	7.245	7.507	6.058	11801	7.483	
270.0	77.96	19.13	10.49	12.09	16.50	28.59	29.62	19.75	201	2421.	73.28
1.494	20.86	4.854	2.660	3.063	4.187	7.249	7.514	6.101	12001	7.506	
270.0	78.18	19.15	10.49	12.09	16.51	28.60	29.64	19.94	201	2421.	73.29
1.519	20.92	4.878	2.661	3.063	4.190	7.253	7.539	6.126	12201	7.529	
270.0	78.39	19.24	10.49	12.09	16.52	28.61	29.73	20.05	201	2422.	73.31

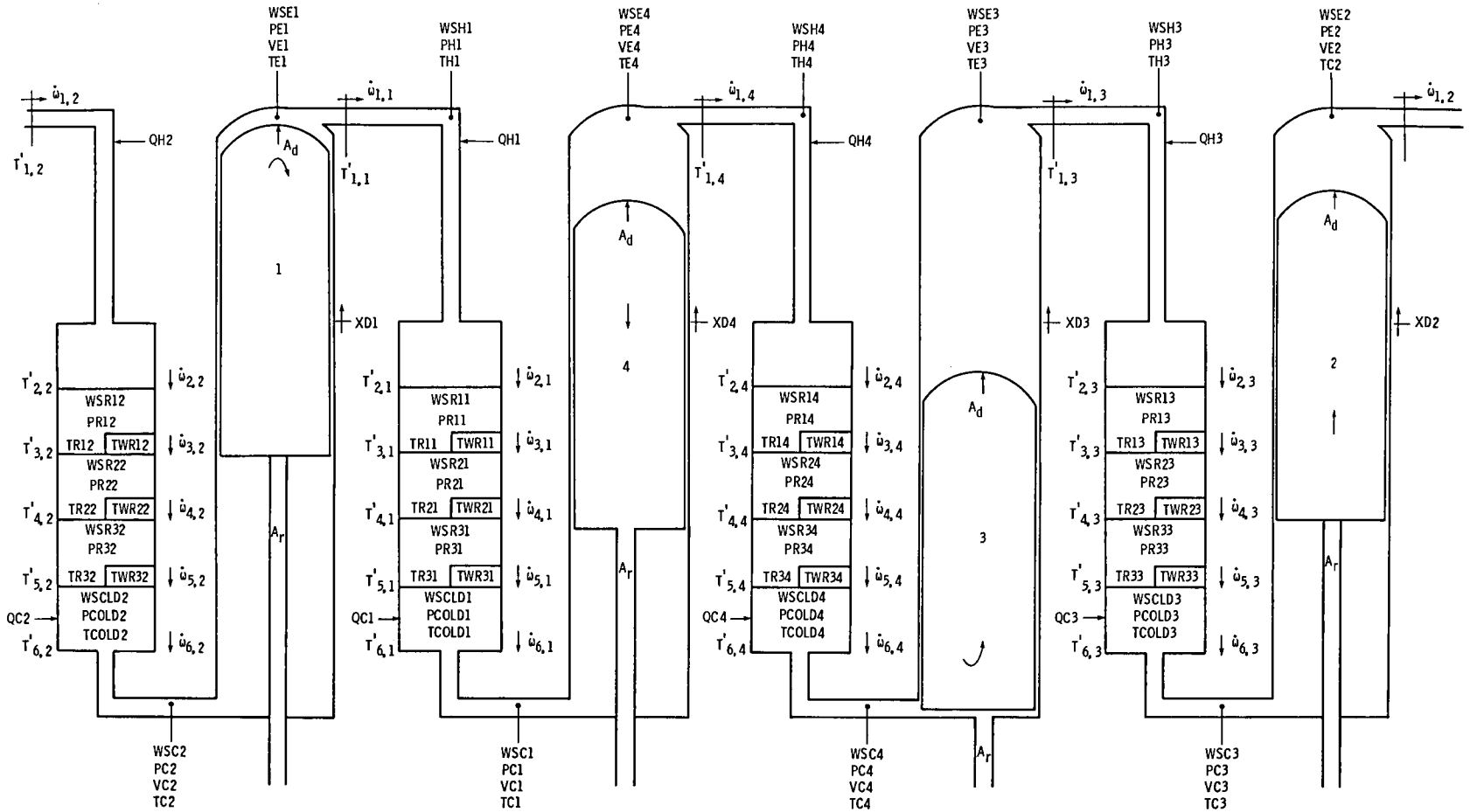


Figure 1. - Four working space model. Last number of a variable name indicates working space; cylinders are numbered in the order that they reach top dead center; primed variables indicate intervolume temperatures.

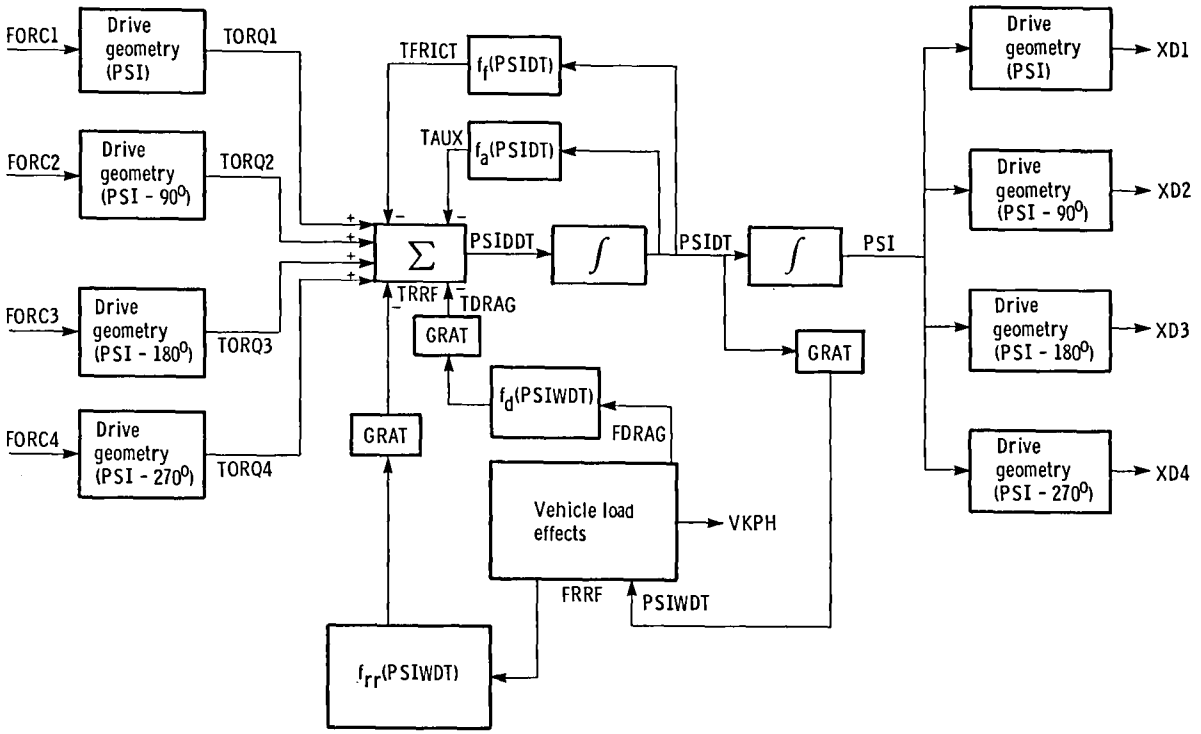


Figure 2. - Stirling engine drive dynamics.

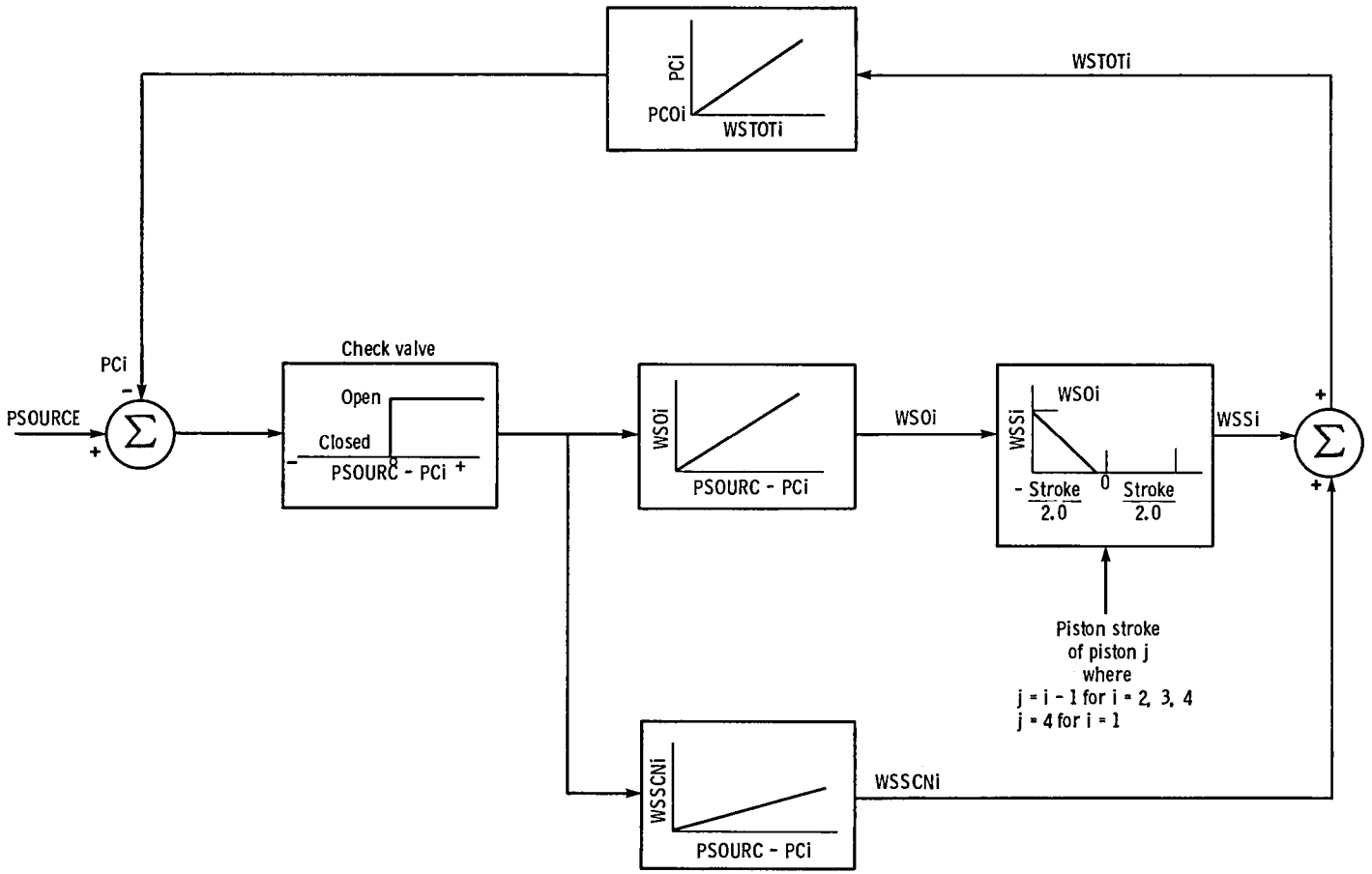


Figure 3. - Hydrogen supply system for compression space i where i = 1, 2 ... 4.

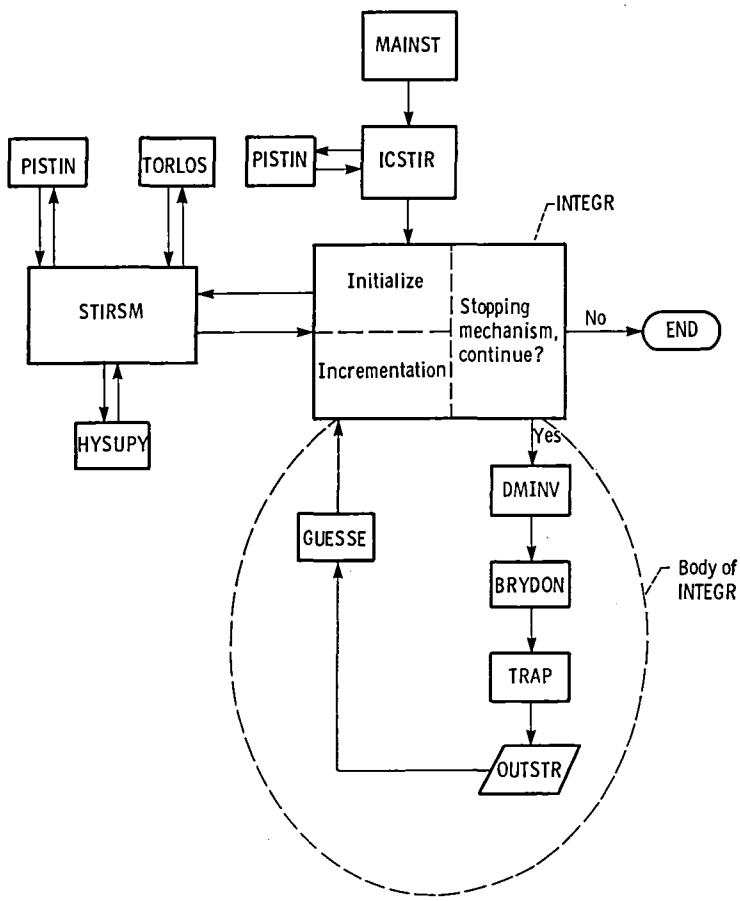


Figure 4. - Overall simulation structure.

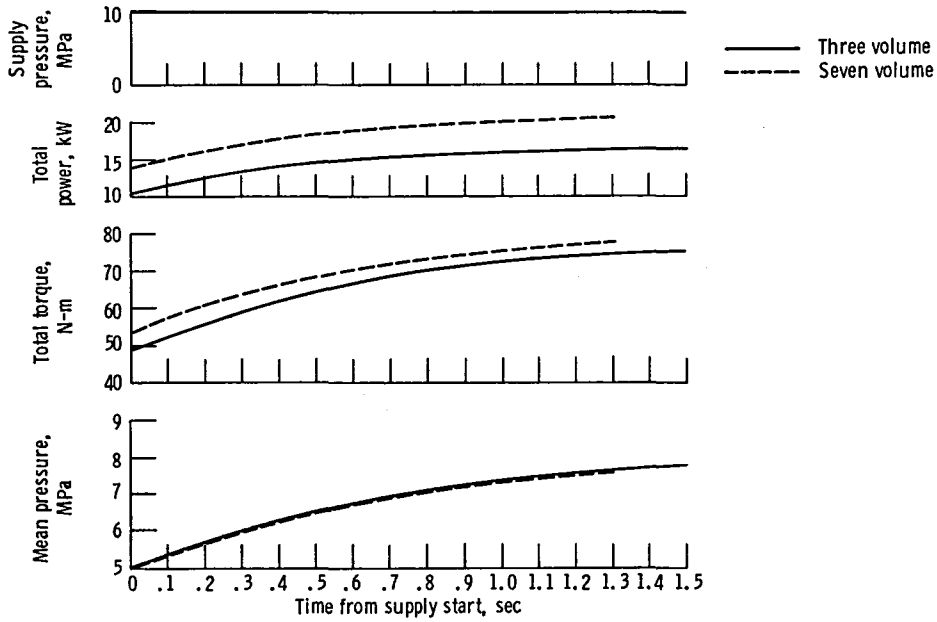
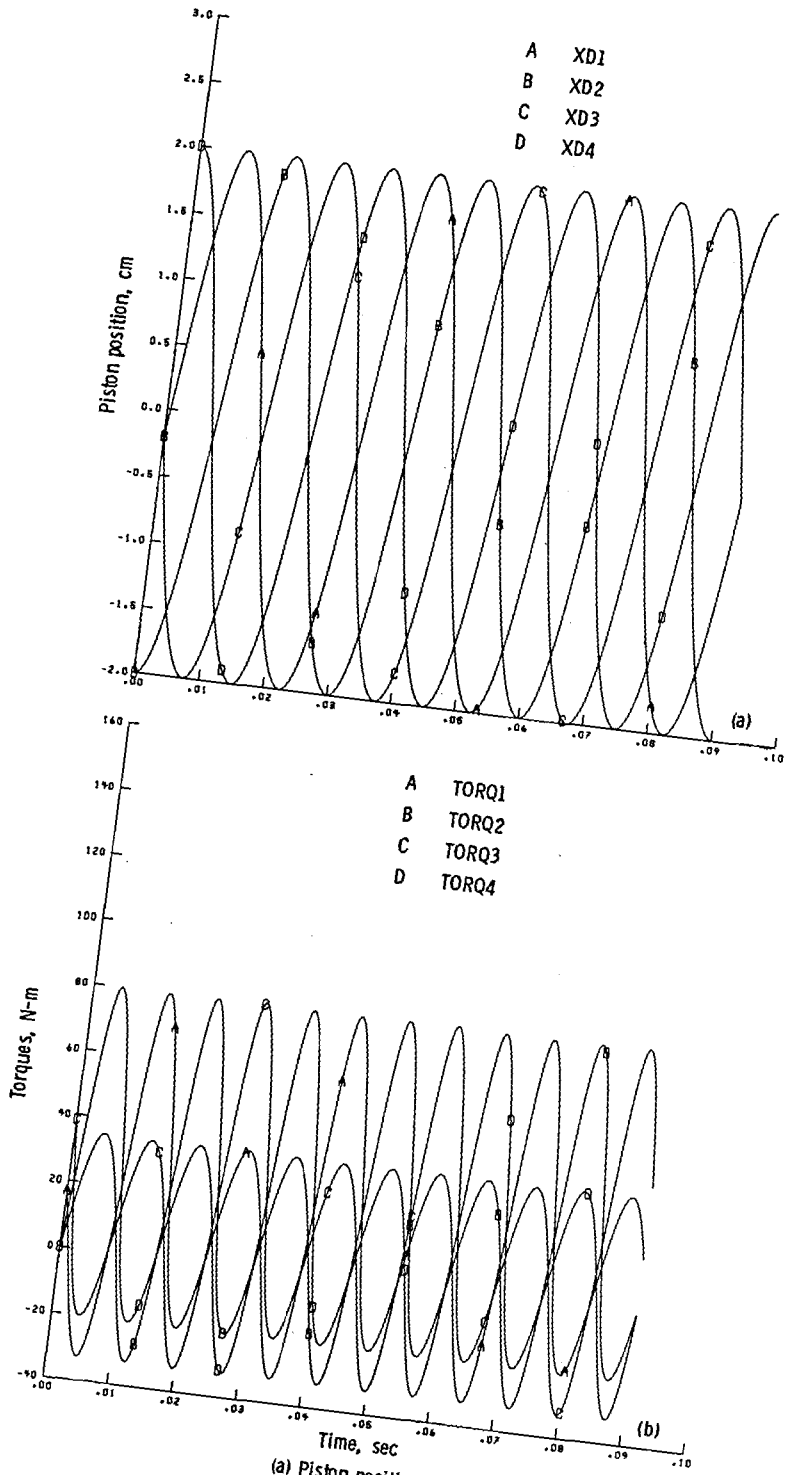
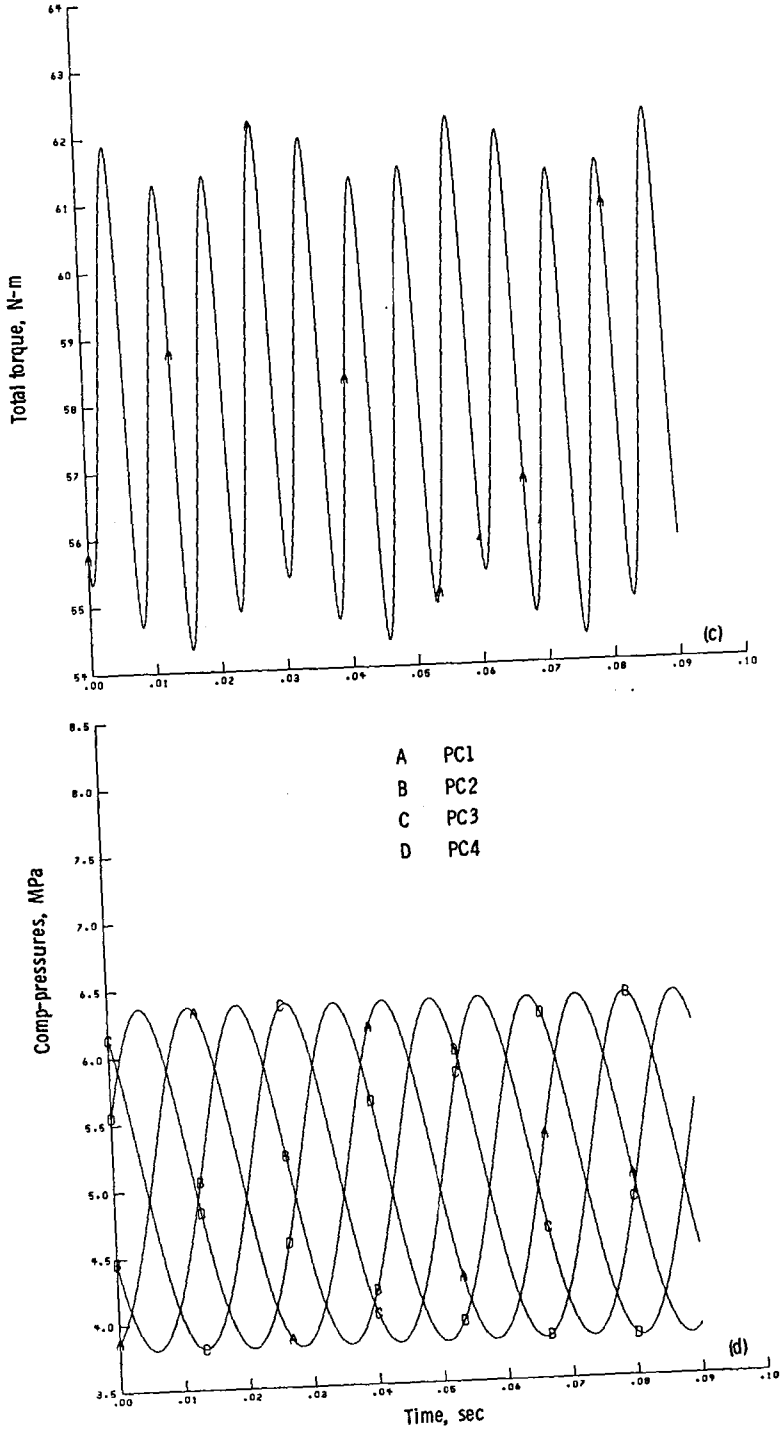


Figure 5. - Simulation results; comparison of complex (seven volume) and simplified (three volume) simulations.



(a) Piston positions.
(b) Individual torques.

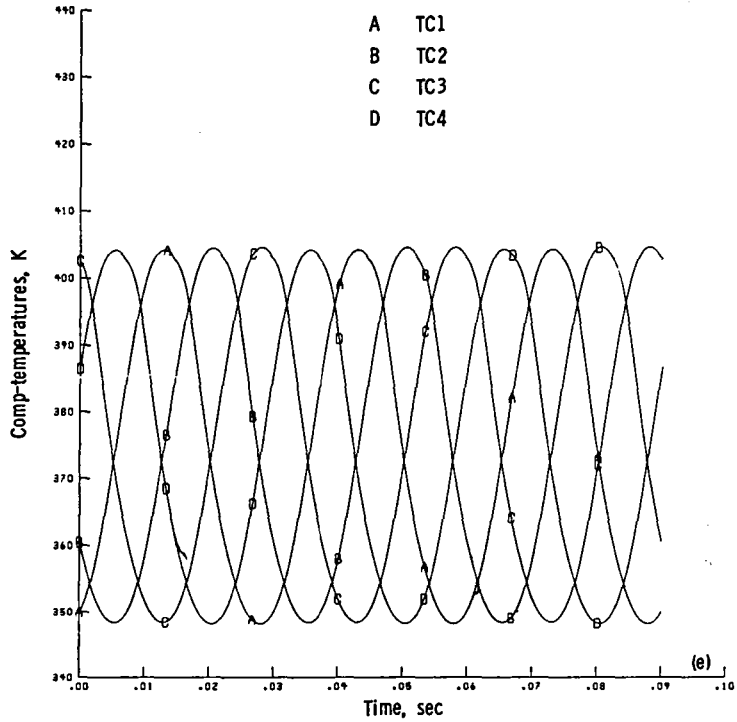
Figure 6. - Steady-state results.



(c) Total torque.

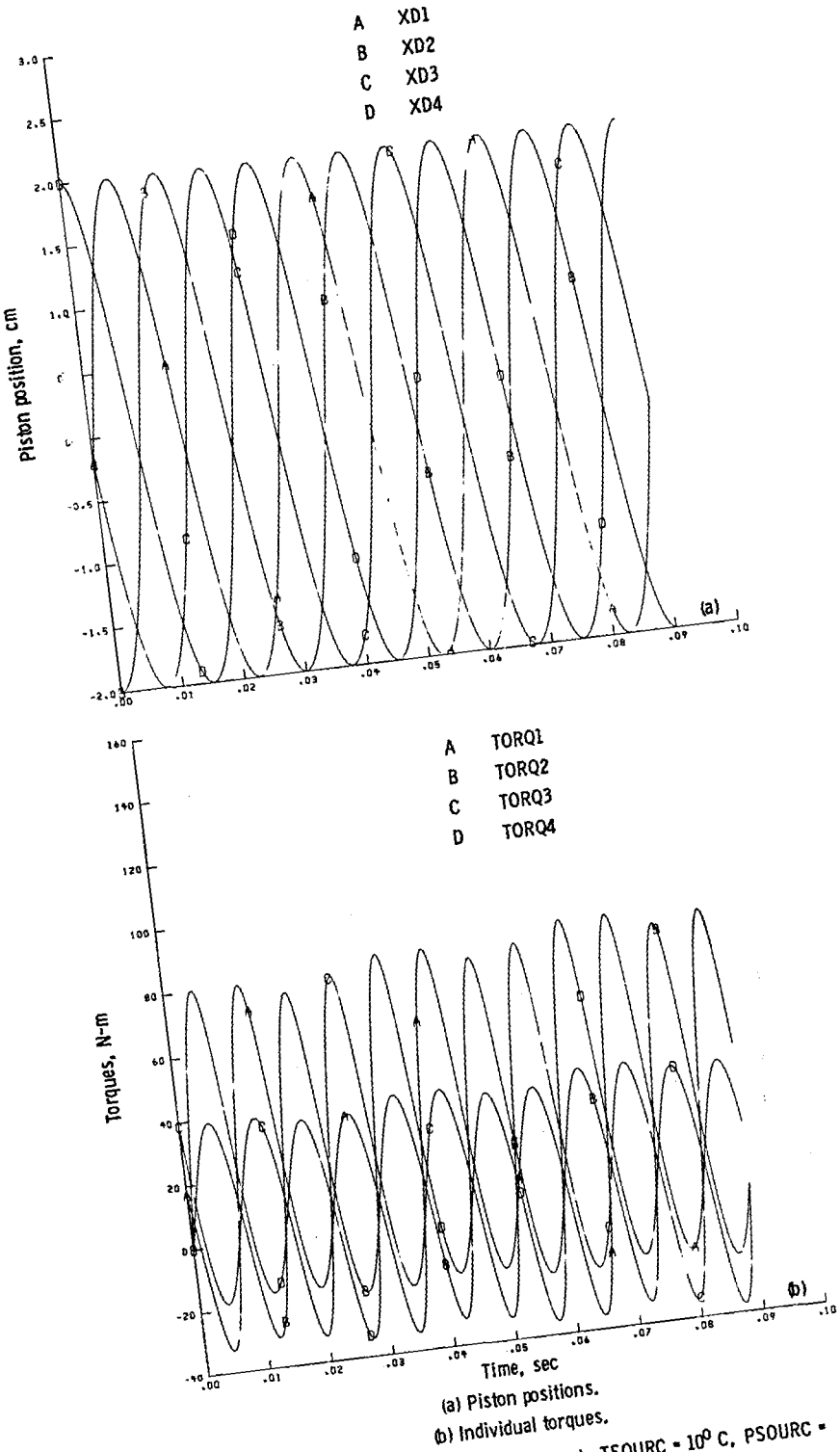
(d) Compression space pressures.

Figure 6. - Continued.



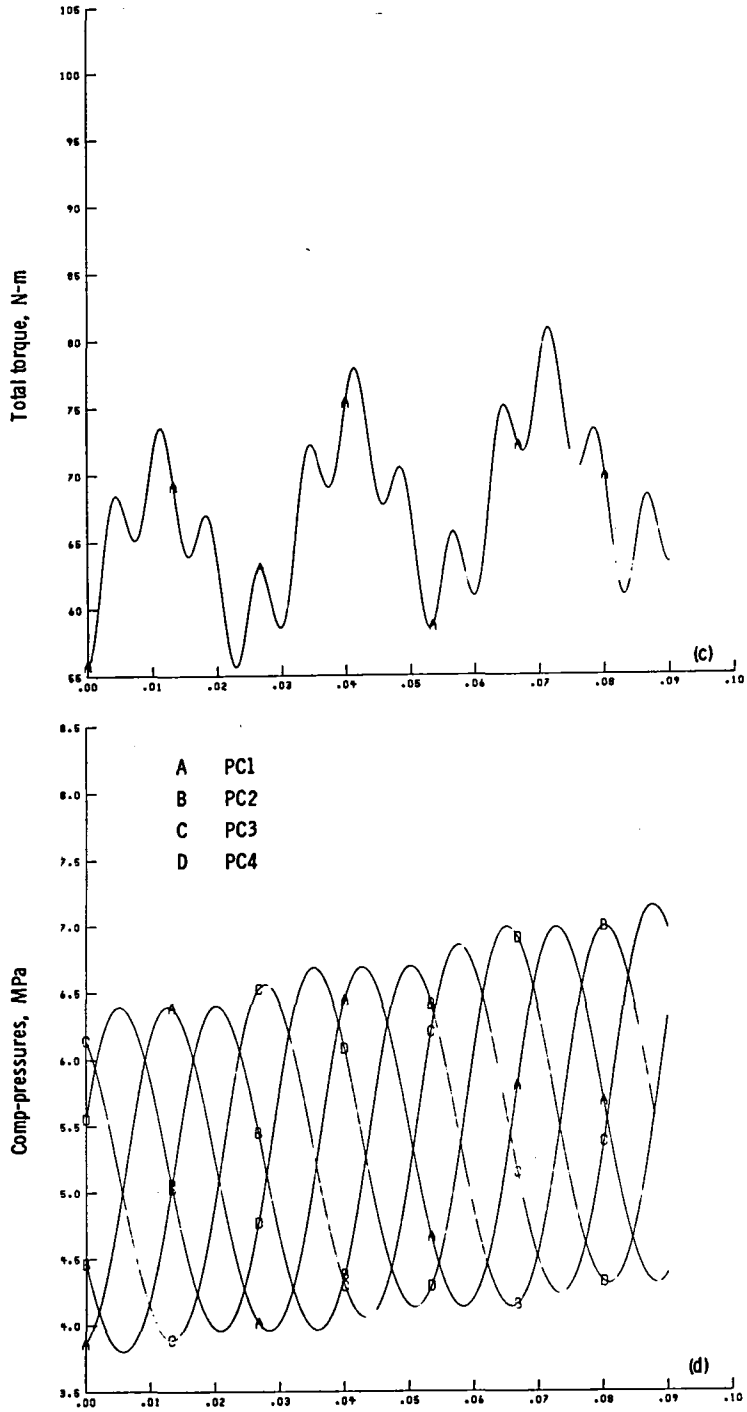
(e) Compression space temperatures.

Figure 6. - Concluded.



(a) Piston positions.
(b) Individual torques.

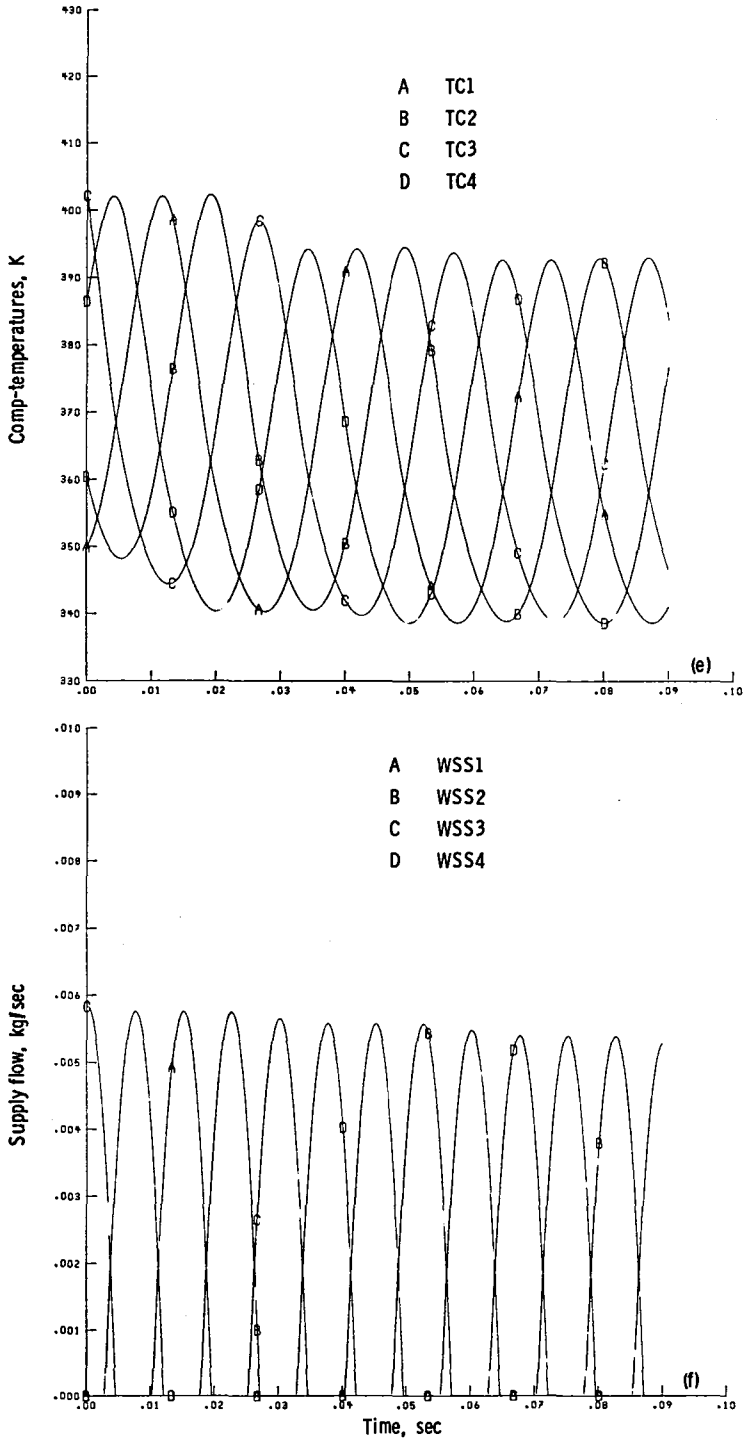
Figure 7. - Supply transient (no rod leakage); TSOURC = 10° C, PSOURC = 10 MPa.



(c) Total torque.

(d) Compression space pressures.

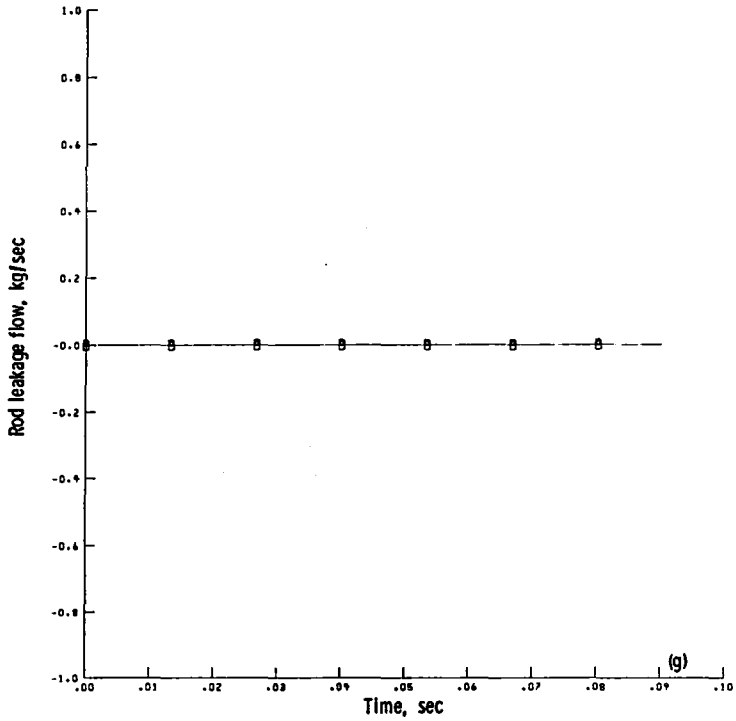
Figure 7. - Continued.



(e) Compression space temperatures.

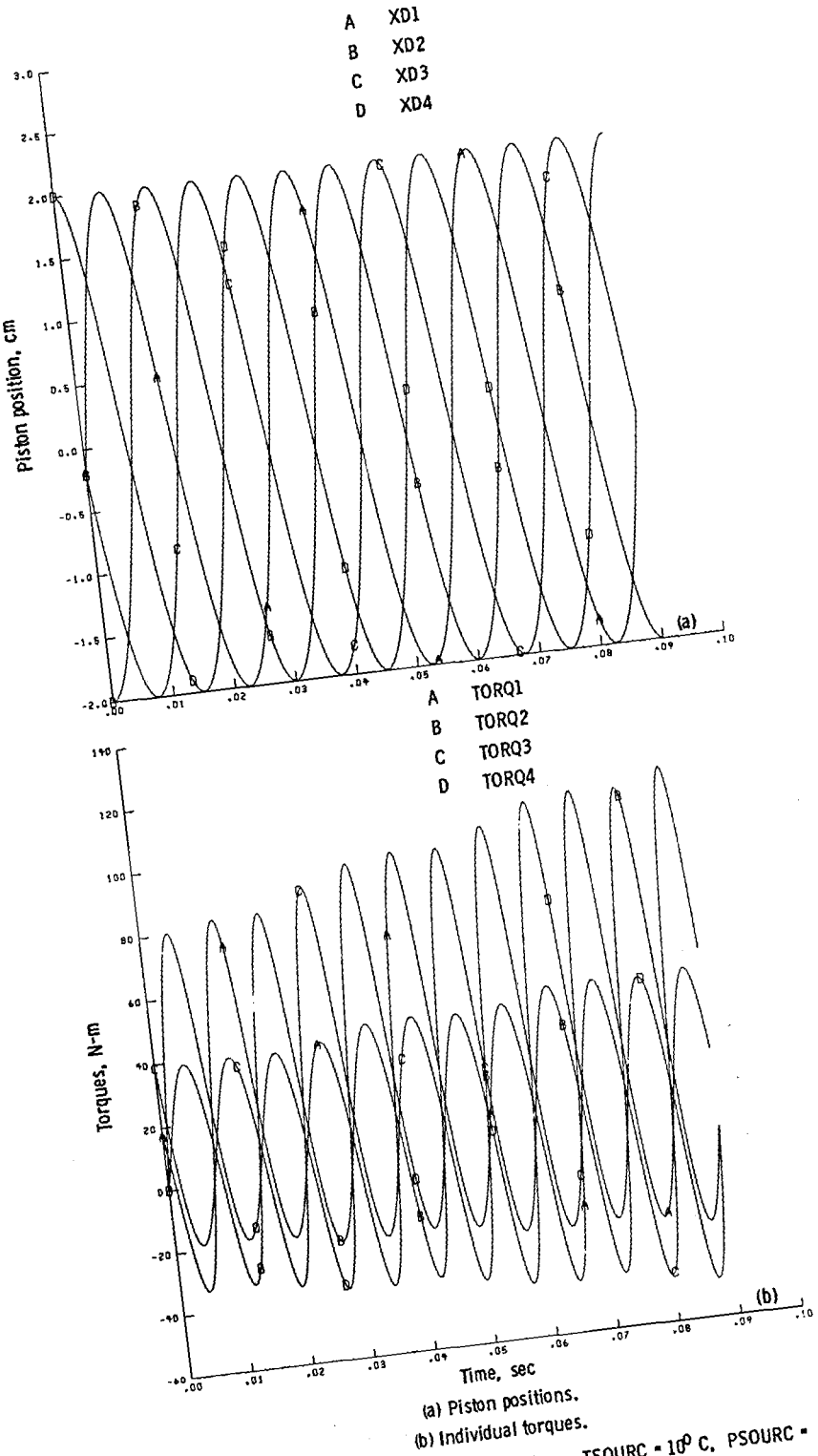
(f) Input supply flows.

Figure 7. - Continued.



(g) Piston rod leakage.

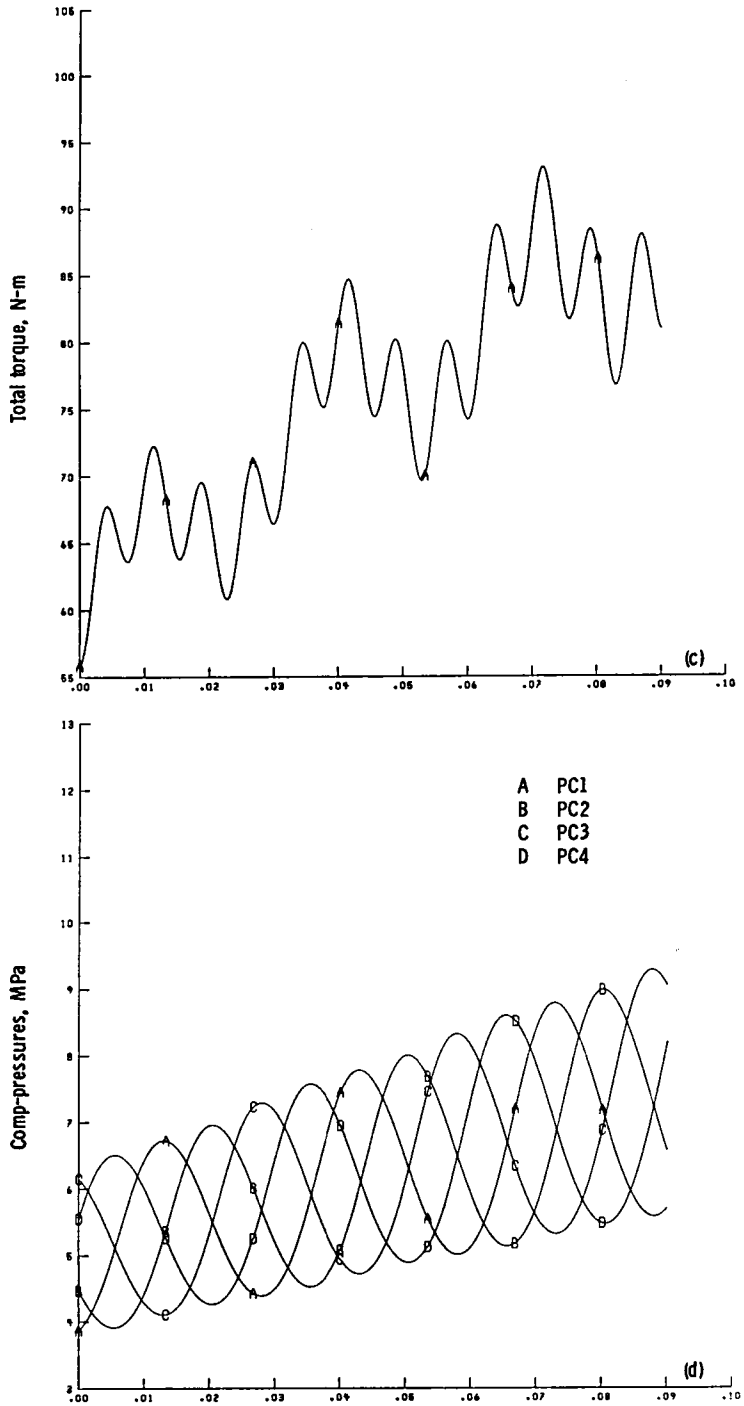
Figure 7. - Concluded.



(a) Piston positions.

(b) Individual torques.

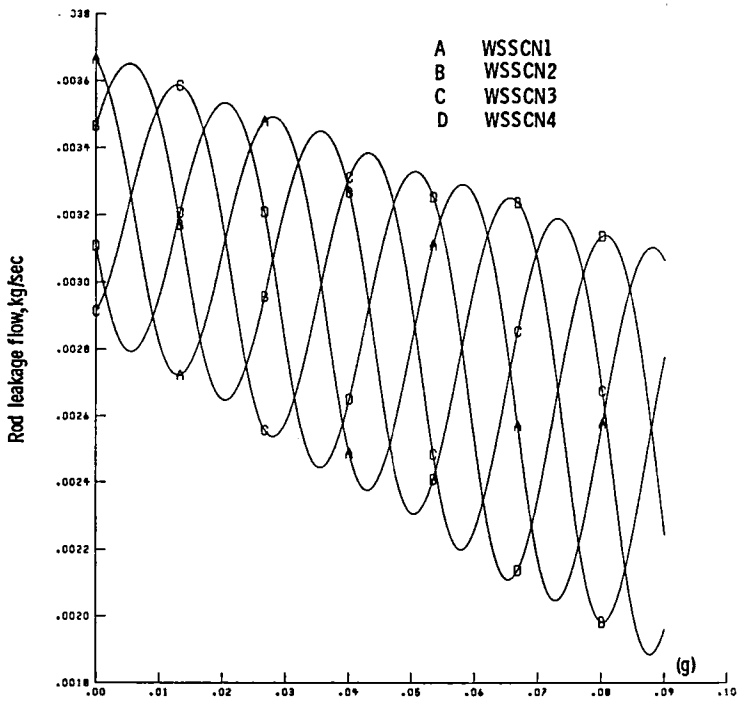
Figure 8. - Supply transient with rod leakage; TSOURC = 10° C, PSOURC = 10 MPa, and ALEAK = 3.23 cm^2.



(c) Total torque.

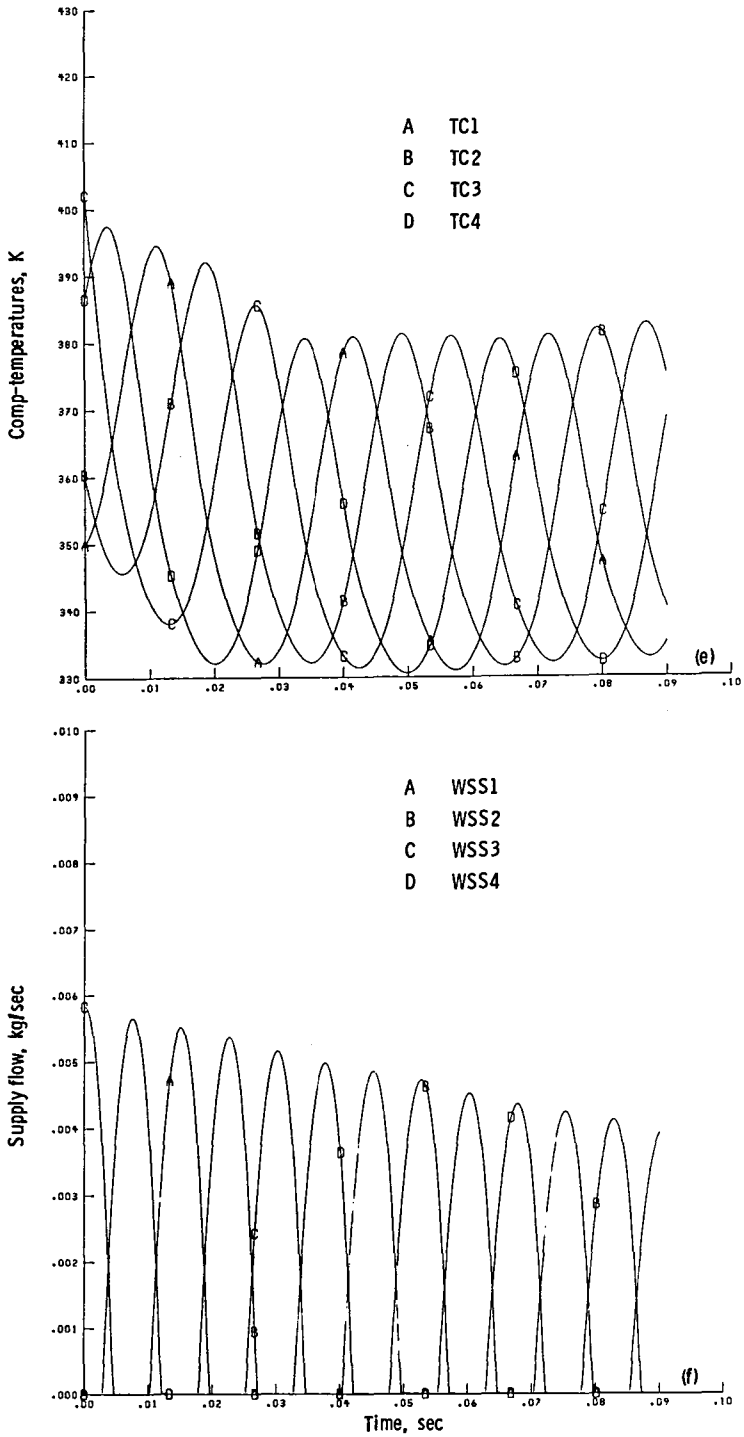
(d) Compression space pressures.

Figure 8. - Continued.



(g) Rod leakage flows.

Figure 8. - Concluded.



(e) Compression space temperatures.

(f) Input supply flows.

Figure 8. - Continued.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83053		

4. Title and Subtitle	5. Report Date
A Four-Cylinder Stirling Engine Computer Program With Dynamic Energy Equations	May 1983
	6. Performing Organization Code 778-35-03
7. Author(s)	8. Performing Organization Report No.
Carl J. Daniele and Carl F. Lorenzo	E-1348
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Vehicle and Engine R&D Washington, D.C. 20546	14. Sponsoring Agency Code Report No. DOE/NASA/51040-44

15. Supplementary Notes

Final report. Prepared under Interagency Agreement DE-AI01-77CS51040.

16. Abstract

A computer program for simulating the steady-state and transient performance of a four-cylinder Stirling engine is presented. The thermodynamic model includes both continuity and energy equations and linear momentum terms (flow resistance). Each working space between the pistons is broken up into seven control volumes. Drive dynamics and vehicle load effects are included. The model contains 70 state variables. Also included in the model are piston-rod-seal leakage effects. The computer program includes a model of a hydrogen supply system, from which hydrogen may be added to the system to accelerate the engine. Flow charts are provided.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Stirling engine Controls Modeling Computer program	Unclassified - unlimited STAR Category 34 DOE Category UC-96

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		A03

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